OAK ROOT AND STEM GROWTH AS INFLUENCED BY AN OZARK FRAGIPAN

by

Charles Kevin Stuart

PREFACE

The research done in the context of this book was done in 1978 and 1979. In 2008, I was sent a copy of my MS thesis by a family member and then decided to make it more widely available in both digital form and hardcopy, hence this version

Charles Kevin Stuart
Honolulu, Hawaii
2009

ACKNOWLEDGEMENTS

I sincerely thank Gene Cox, Bob Blanchar, Clarence Scrivner, Gray Henderson, Dave Moorheard, Alan Black, Alice Walters, Nell Cox, Randy Leutzinger, Liesa Mannbeck, Prudence Black, C. Pham, Bob May, Jerry Gott, Zainal Bahari, Bob Teskey, Laurie Neill, Ron Renkoski, Sam Feagley, Calvin Ainsworth, John Roberts, Paul Szopa, Jim Burroughs, Dick Smith, Bob McQuilkin, Chuck G. Lamb, Fred and Ida Leonhard, Fred Kaiser, Bill Minor, Mary Stuart, Nona Angwin, Jim, Judy, Ed Langwig, T.H. Silker, Dave Robinson, Kur Antono, Madi Chushnun, Barb Black, Anton Kusuma, and Ocky Tjakara.

CONTENTS

TABLES

FIGURES

INTRODUCTION

Fagipan soils are commonly considered to be detrimental to plant growth because of their density and acidity that inhibit the downward growth and development of plant roots. These fragic horizons are significant soil features in much of the United States, and because much of this area is tree-covered they are of particular interest to foresters. In Missouri, fragipans are found predominantly south of the Missouri River and according to one estimate, comprise approximately nine percent of the soils of the state (Edmonds 1976).

As the worldwide demand for timber and wood-derived products continues to increase in the decades ahead, it is imperative that we better understand those relationships responsible for the low productivity of such soils. With greater understanding comes the opportunity for increasing the supply of one of man's most basic and valuable resources.

This study examines the relationship between tree growth and fragipan soils on an upland forested site in south-central Missouri by asking these questions:

- Is there a fragipan on the site and, if so, is there a relationship between fragipan expression and landscape position?
- Are there significant differences in soil chemical and physical properties on the study site and, if so, how do these differences relate to the presence or absence of the fragipan?
- Are there significant differences in the root distribution patterns of trees growing on soils with a fragipan as opposed to those growing on soils without a fragipan?

- Do trees growing on fragipans grow fairly well until a certain age and then decline markedly in growth?

LITERATURE REVIEW

> Excellence in the production of great art may require years of dedicated commitment to creative interchange between the artist's practice of intrinsic perception and the material, such as sound in music, color in painting, students in the professional art of the teaching-learning process, soil in the industrial art of agriculture, or electricity in the art of electrical engineering. *William S. Minor*

The purpose of this section is not to thoroughly review literature related to fragipans–that was done adequately by Grossman and Carlisle (1969)–but rather, to give some general background information about fragipans.

Definition

The term 'fragipan' comes from the Latin *fragilis* and translates literally as 'brittle pan'. It was proposed by G.D. Smith in 1946 and was later adopted by the Soil Survey Staff of the U.S. Department of Agriculture (Grossman and Carlisle 1969, Soil Survey Staff 1975).

The Soil Survey Staff (1975) defines a fragipan as:

> "…a loamy or uncommonly a sandy subsurface horizon that may but not necessarily underlie a cambic, spodic, argillic, or albic horizon. It has a very low content of organic matter, has high bulk density relative to the horizons above it, and is seemingly cemented when dry, having then hard or very hard consistence. When

> moist, a fragipan has moderate or weak brittleness, which is the tendency for a ped or clod to rupture suddenly when pressure is applied rather than to undergo slow deformation. ... A fragipan is usually mottled, is slowly . . . permeable to water, has bleached, roughly vertical planes that are faces of coarse or very coarse polyhedrons or prisms, . . . has an abrupt or clear boundary at a depth of 33 to 100 cm below the original surface, (is) 15 to 200 cm thick, . . . (and is) virtually free of roots except along the bleached faces.

Other definitions have been offered but all point to the presence of common soil properties: (1) high bulk density, (2) low pH, (3) a polygonal structure, (4) very few roots, (5) low clay content, and (6) brittleness under stress. As might be expected, the identification and subsequent classification of fragipans is problematic because of the relativity of brittleness (Hallmark and Smeck 1979b) and root frequency, considerable variation in texture, density, and structure and position in the profile. This tends to place the burden of identification on the field observer. Steele et al. (1969) discussed some of these difficulties:

> The decision as to the presence of a fragipan in some Ultisols must rest entirely on the presence of brittle bodies. We have no other choice under the present definition of a fragipan, but cannot improve on this definition. Identification of brittleness under all field conditions is far from satisfactory; it varies in degree as well as in horizontal and vertical distribution.

The soil mapper has the problem of identifying brittleness under varying moisture conditions at any depth in the solum, as well as the problem of delineating areas where the brittle pan materials are discontinuous. He must also distinguish the brittleness of fragipans from that of prismatic materials.

Geographic Extent of Fragipan Soils

Fragipans have been recognized in soils on all continents except Antarctica (Olson and Hole 1967-1968). In the USA, fragipans have been identified in soil in every state east of the Mississippi River (Figure 1) and in Minnesota, Missouri, Arkansas, Oklahoma, Louisiana, and eastern Texas (Grossman and Carlisle 1969). Although fragipans have been reported in certain of the western states, the occurrence of soils with fragipan horizons there seems to be rather limited (Table 1).

The approximate boundaries for fragipan expression in Missouri are as follows (Scrivner I960): Northern–the Missouri River, western–exposures of Pennsylvanian shale and carbonate rocks of the Pennsylvanian shale and carbonate rocks of the Mississippian system, and southern–fragipans are found through the southern part of Missouri into Arkansas. The Lebanon, Hobson, and Nixa are examples of soil series in Missouri that have fragipans. These are (or originally were) forested, highly weathered soils situated on nearly level to gently rolling topography interspersed with steeply sloping areas bordering drainages and streams (Scrivner et al. 1975).

Genesis

Although there may be a number of different processes that contribute to fragipan formation, Grossman and Carlisle (1969) point out four relationships evident in the broad-scale occurrence of fragipan soils: (1) fragipans are restricted to areas where precipitation exceeds evapotranspiration in sufficient quantity to permit movement of water down through the soil during some time of the year; (2) fragipans occur in both warm and cold climates; (3) fragipans seemingly are absent in soils of the extensive grasslands of the humid prairies and the Great Plains. Trees are the principal vegetation on fragipan soils. (4) Fragipans occur in Spodosols, Inceptisols, Alfisols, and Ultisols with an association so common with the Spodosols as to suggest a genetic connection.

Figure 1. Areas in the United States where one or more of the principal kinds of soils have fragipans. The most extensive soils in the areas delineated are: A, Alfisols; I, Inceptisols; S, Spodosols; U and U2, Ultisols. The dashed line shows the approximate eastern boundary of the prairie (from Grossman and Carlisle 1969).

Table 1. Extent of soils with fragipan horizons in the United States (from Edmonds 1976).

Area			
Area	Total soils	Fragipan soils	Percentage of state
Northeast			
Connecticut	3,122,160	940,000	30.00
Delaware	1,265,883	9,551	0.80
Maine	19,848,000	9,400,000	49.00
Maryland	6,319,000	398,949	6.30
Massachusetts	5,033,000	1,006,600	20.00
New Hampshire	5,769,000	945,000	16.00
New Jersey	4,810,000	335,000	7.00
New York	30,670,000	10,135,000	33.00
Pennsylvania	28,797,500	8,545,141	30.00
Rhode Island	677,120	225,000	33.00
Vermont	5,937,293	1,460,251	25.00
Virginia	25,458,000	1,000,000	4.00
West Virginia	15,402,000	820,000	5.30
South			
Alabama	32,697,000	488,517	1.50
Arkansas	13,586,000	2,671,940	8.00
Florida	34,721,000	0	0.00
Georgia	37,217,000	111,540	0.30
Kentucky	25,405,000	3,184,040	12.50
Louisiana	28,862,000	1,274,350	4.40
Mississippi	30,222,000	4,191,920	13.90
Oklahoma	44,075,000	391,500	0.90
South Carolina	19,370,000	222,000	1.20
Tennessee	26,478,000	2,305,450	8.70
Texas	168,300,000	666,000	0.40
West			
Alaska	362,516,480	290,013	0.08
Idaho	52,913,280	317,480	0.60
Oregon	61,557,760	123,115	0.20
Washington	42,604,800	29,823	0.07

Area			
Area	Total soils	Fragipan soils	Percentage of state
Midwest			
Illinois	35,678,720	1,339,930	3.70
Indiana	23,102,080	1,464,000	6.30
Michigan	36,362,880	1,700,000	4.70
Missouri	44,189,300	3,977,000	9.00
Ohio	26,205,600	2,233,538	8.50

Hallmark and Smeck (1979a) identify two prevalent theories that explain the morphology and genesis of fragipans: (1) fabric rearrangement as a result of periglacial climates; and (2) soil genetic processes affecting fabric rearrangement committed with either physical binding by clays or formation of weak chemical bonds. Because fragipans are frequently found outside the range of historical glacial activity (southern Missouri, for example), it is doubtful all fragipans were formed by the weight of glacial ice or by frost activity. Nevertheless, in areas of historical glacial activity, processes associated with the phenomenon probably contributed to the formation of the fragipan (Fitzpatrik 1956).

In unglaciated areas the second theory is prevalent. Zachary and Ulrich (1965) suggest a scenario for pan formation in three soil types found in southern Indiana: (1) deep loess or windblown silty material, (2) thin loess over Illinoian age till, and (3) thin loess over residuum material that are products of the disintegration and decomposition of limestone and interbedded sandstone and shale. The last of these three is the category into which the pan examined in this study would fall:

It is theorized by some workers that at the beginning wetting and drying and freezing and thawing would loosen the surface layer and make it more porous and permeable and a better medium for plant growth. As plants and animals become established, organic matter accumulates at the surface and gradually becomes mixed with the mineral soil to form the A1 (topsoil). At this stage it seems most likely fresh deposits of silty parent, or silt forming material, occurred, starting a new cycle of soil development. Decay and solution of the organic matter removed the protective coating on the iron oxides and clay favoring movement with the ground water. The gel-like oxides of iron and A1 move downward plugging the pores and increasing the density of the pan. Leaching of bases would be most intense immediately above the less permeable subsoil, so the horizon with the gray silt coatings would begin to develop. This gray silt cap horizon is present just above the fragipan.

Over a period of years, during dry late summers, the soil material would shrink and crack into blocks with many sides to a depth of 3 or s 4 feet. Mater moving downward carries fine sand, silt and clay from the upper horizon and deposits them along the cracks in the lower horizons. These deposits form planes of weakness so that subsequent cracking will always occur in the same place. The pore space between the medium blocky peds eventually fills with fine material, and the blocks adhere to one another to form large dense,

> nearly massive prisms. From then on when the horizon dries out most of the cracking will occur at the boundaries of the large prisms. Thus depositions of fine material in these cracks could be the origin of the gray streaks. Intense leaching will cause the soil to become strongly acid. The continuous drying and wetting and filling of the cracks with compression upon wetting could explain the much higher bulk density of the fragipan.

Yassoglou (1959) working with soils in northern Michigan containing fragipans suggested that the most important factor of induration was the close packing of sand and coarse silt grains cemented together by an optimum clay content in the form of clay bridges. He offered the following hypothesis for fragipan development:

> In the preceding discussion we have shown that close packing of the sand and silt grains, a certain optimum clay content and a proper arrangement of the soil particles are the main factors responsible for the induration of the pan. . . . The genesis of the fragipan horizons takes place parallel to the genesis of the other horizons. After the leaching of the carbonates and acidification of the profile, the following steps are postulated for the formation of the pan: (a) Removal of a part of the clay fraction and preferentially of the expanding clay. (b) Contraction following the removal of clay step by step. This contraction which resulted in the close packing of the grains was gradual and not uniform. Forces which caused this

contraction were the gravitational forces within the horizon, the load of the overlying horizons, pressures exerted by the roots of the trees, and pressures developed during wetting and drying plus freezing and thawing of the soil during the early stages of development. The contractions, therefore, caused by forces acting at different directions resulted in a three dimensional shrinkage of the pan and in the formation of vertical cracks and the coarse columnar structure. It is known that the formation of a hexagonal pattern of cracks caused the least cracking due to shrinkage.

In case of a uniform body being gradually contracted from the top to the bottom a hexagonal prismatic structure is produced. In this way the formation of polygonal patterns of cracks found in many fragipans throughout the country . . . can be explained, occurrence Following the contraction and the close packing of the skeletal elements, the matrix substances (fine silt and remaining clay) undergo a rearrangement.

The close packing of the sand has provided the capillary interangular spaces, in which the soil suspension is confined at moisture levels below field capacity. Upon evaporation of the water, the clay is deposited forming optically anistropic menisci which serve as bridges connecting the neighboring sand and coarse silt grains. (d) During the course of the soil development, aluminum is released from the decomposing minerals, and a part of it is precipitated from the soil solution in the area

of the pan, possibly adding to the cementation of the pan.

Both schemes for understanding the process of fragipan formation are similar in that both postulate intense leaching, removal of clay, formation of cracks, and a period of contraction that ultimately leads to the dense fragic structure.

THE STUDY SITE

Location

The study site was located on a broad ridge on the Mark Twain National Forest in the Ozark Highlands of south-central Missouri. The site was approximately 8.3 km (5.2 miles) southeast of Newburg, Missouri, on Missouri State Highway P in Phelps County.

Past History

The remains of an old road and decaying stumps suggested that the site had been logged sometime in the past. Additionally, the site had been burned and probably had been subjected to the grazing of domestic livestock. These conditions prevail throughout the Ozark Region in general.

Vegetation

Post oak (*Quercus stellata* Mangenh), blackjack oak (*Quercus marilandica* Muenchh.), black oak (*Quercus velutina* Lam.), and white oak (*Quercus alba* L.) comprised the dominant overstory vegetation. The understory was largely dogwood (*Cornus*), sassafras (*Sassafras albidum* (Nutt.) Nees.), hickory (*Carya*), shortleaf pine (*Pinus echinata* Mill.), and the aforementioned oaks.

Pit Layout

Eight pits were excavated with a backhoe along a 112 m transect whose compass bearing was N56°E (Fig. 2). Each pit was dug to a depth of approximately 150 cm (or until bedrock was encountered) and located so that the center of each pit was 1 m from the base of a preselected dominant oak tree. Pits were placed so as to sample two soils without fragipans, two soils which were transitional between soils with and without fragipans, and four soils with fragipans. However, the profile of pit 2 was much the same as the profile of pit 1 in that neither had a fragipan; therefore, pit 2 was not used in the study. The following list classifies each profile as to the presence or absence of a fragipan:

- Profile 1 no fragipan
- Profile 3 transition from no fragipan to fragipan
- Profile 4 fragipan
- Profile 5 fragipan
- Profile 6 fragipan
- Profile 7 transition from fragipan to no fragipan
- Profile 8 no fragipan

Soils

Soils on the site are highly weathered and have developed under a forest vegetation. Two parent materials are present: Roubidoux sandstone and Wisconsin age loess. Mr. Jerry Gott (Soil Scientist, USFS, Rolla, Missouri) and several soil scientists associated with the Soil Conservation Service visited the site and described the seven profiles. These field descriptions are given in Appendix A. Two descriptions are included for profile 6 as this profile was described

independently by two individuals.

Soils in profiles 1 and 8 were classified as clayey, mesic, Typic Hapludults and soils in profiles 4,5, and 6 were classified as clayey, mesis Aquic Fragiudults. Pits 3 and 7 were transitional in nature, and therefore were not placed in either of the above classifications.

Fragipan Study Site in the Mark Twain National Forest. Fragipan Boundary = ▬; Soil Pits = 1-8; Elevation (ft) = 980.

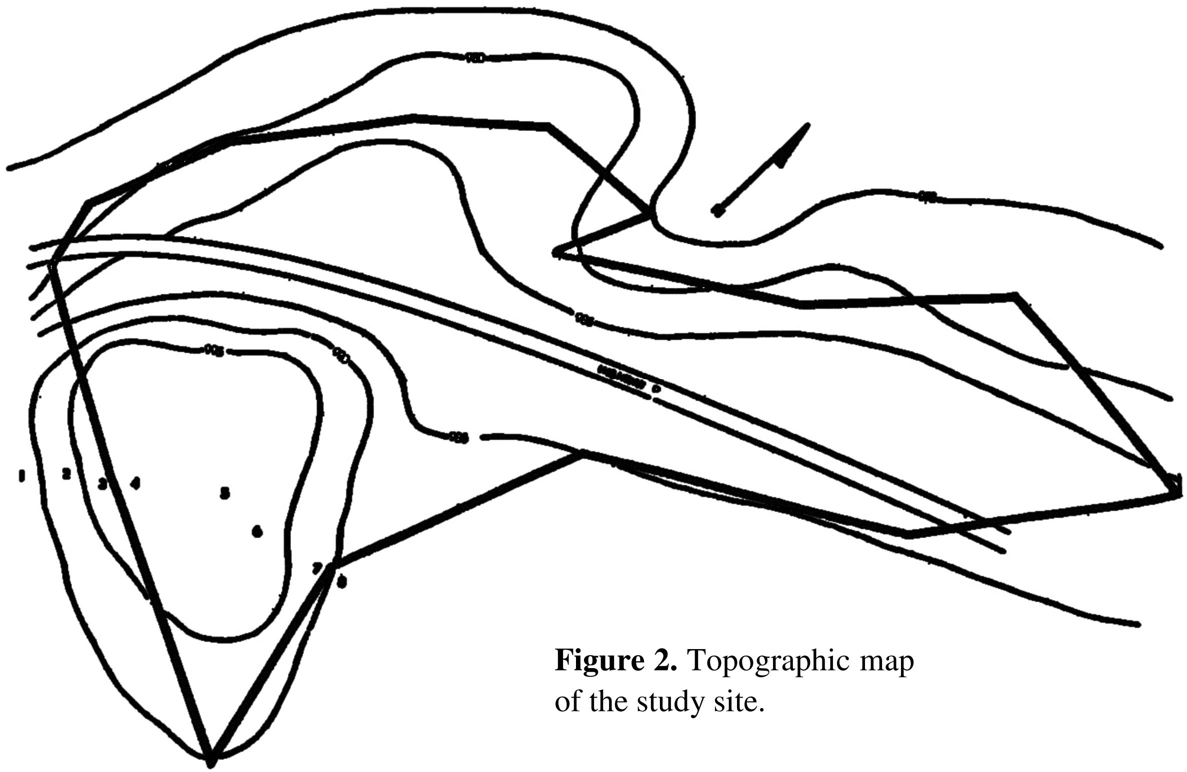


Figure 2. Topographic map of the study site.

FRAGIPAN EXPRESSION AND LANDSCAPE POSITION

In many areas, the fragipan is confined to topography that is nearly level to gently sloping. As the slope percentage increases, the fragipan seems to disappear. Because of this relationship, that area of the forest that is the most easily harvested and replanted from a mechanical standpoint is also the area with a fragipan. This part of the study was undertaken to more closely define the relationship between fragipan expression and landscape position.

Literature Review

Fragipans occur on a variety of landscapes and on a variety of positions on a given landscape. In a description of a glaciated valley in central New York, Hanna et al. (1975) discussed the presence of a fragipan. In the landscape they examined the well-drained soils of the broad, gently sloping summit area (Figs. 3a and 3b) lacked fragipan development. The lack of a fragipan was attributed to the presence of bedrock within 1 m of the surface. On the shoulder, backslope, and footslope segments of the hillside, where the till mantle exceeded 1 m, fragipans classified as Typic Fragiochrepts were observed. Fragipan soils extended through the toeslope component of the hillside (Aerie Fragiaquepts) into the high level terraces of the valley bottom (Typic Fragiochrepts), but did not extend into the intermediate level terraces which had formed in well-stratified alluvial sediments.

Lack of fragipan development in the fluvial terraces was thought to be related to the relatively low content of very fine sand and silt, good drainage, and the age of the deposits.

Winters (1942) in a discussion of ‘silica hardpans’ in Tennessee, Mississippi, Alabama, Kentucky, and Illinois

suggested that they occur, "...in soils developed on the smoother relief, with slopes of less than 10 percent..."

Smith and Browning (1946) in a description of 'siltpan' subsoils in West Virginia reported: "Strong and well-defined siltpans occur primarily on slopes of five per cent or less..." Lyford and Troedsson (1973) in their study of a Spodic fragipan in Sweden wrote: "

> The well drained soils...have well expressed fragipan horizons and are representative of rather extensive areas of similar soils in Sweden. The soils are immediately above the postglacial shore line. ... Convex areas on the gently rolling landform are 100-200 meters across and have 2-10 percent slope gradients.

Again, the idea is one of fragipans on gentle slopes. Miller et al. (1971) described a fragipan typical of northeastern Ohio and northwestern Pennsylvania (Canfield silt loam) as occurring on moderate relief, "...with gentle undulating slopes occurring at elevations of about 365 m (1.200 ft.). Often the slopes are long some exceeding 300 m."

From the Coastal Plain, Prasad and Perkins (1978) wrote, "... soils containing fragipans or having fragic characteristics constitute more than 250,000 ha of the Southern Coastal Plains Soil Province…occur on relatively level to gently sloping topography."

In Missouri, Krusekopf (1942,1963) described fragipans in the Ozark Region as "…characteristic of the level and gently rolling ridge and plateau areas…" and again as common "…on ridges and on slopes of less than 10 percent..." F1etcher and McDermott (1957) described a fragipan common to the southeastern Missouri Ozarks as being on gently rolling upland terrain with a slope of five percent.

Figures 3a and 3b. Hillslope and cirque-like basin of Hemlock Creek watershed; profile morphology related to geomorphic components (from Hann et al. 1975).

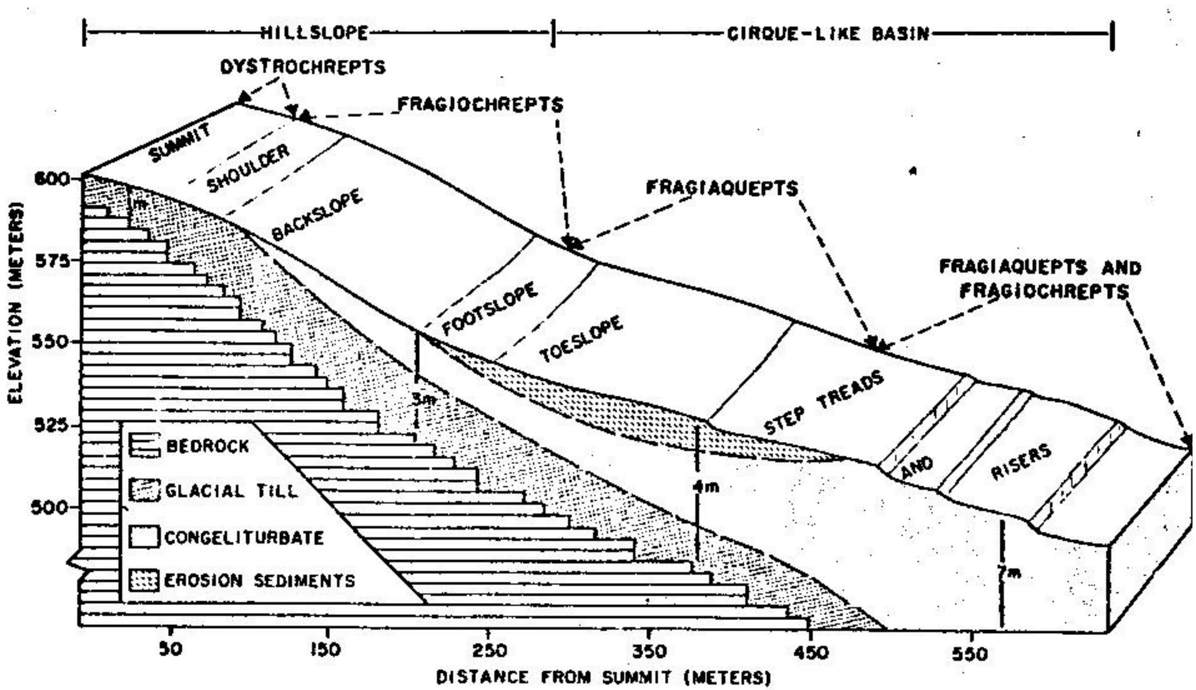
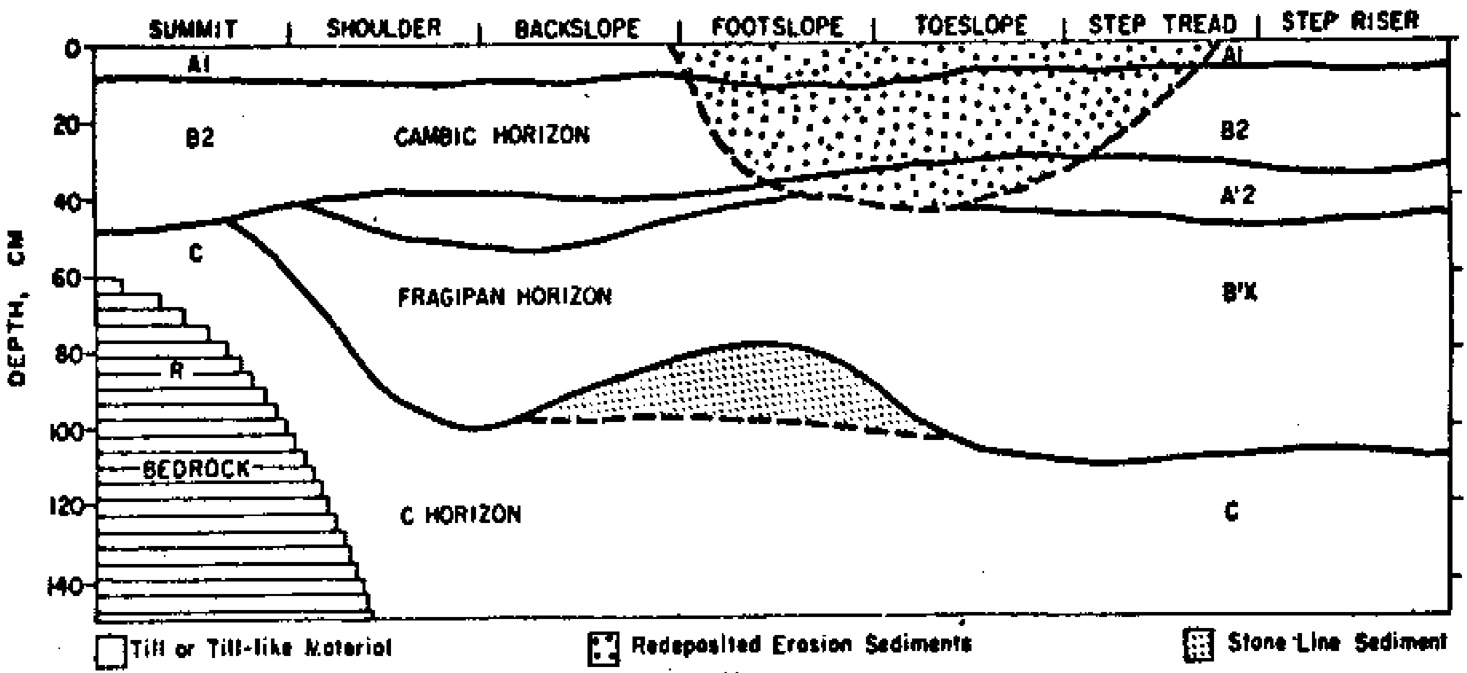


Figure 3a. Hillslope and cirque-like basin of Hemlock Creek watershed.

Figure 3b. Profile morphology related to geomorphic components.



To conclude, the literature suggests fragipans are usually found on level to gently sloping topography, with slopes of less than ten percent. The precise location of a fragipan on a particular landscape depends on such factors as depth to bedrock and drainage.

Basic Question

Does a fragipan exist on the study site and, if so, what is the relationship between pan expression and landscape position?

Methods and Materials

The study site occupied a broad, level to gently sloping ridgetop. An initial soil pit revealed the presence of a fragipan. Subsequently, a porthole digger was used to locate the boundary between the soil with a fragipan and the soils without a fragipan. This was done by visually estimating where on the landscape the fragipan would end and then digging a hole to see if a pan was present. If a pan was Found, I moved down the slope and continued to dig holes until I found a hole in which the pan was absent. If the first hole revealed no pan, then I would move up the slope and continue digging until a soil with a pan was found. The distance between the last two holes dug (pan and nonpan) was usually twenty feet or less. A stake was then driven in the ground halfway between the last two holes dug. A traverse of the ridgetop was made on which the elevation occurrence lower boundary of the fragipan was determined at eighteen points. The distance between adjacent points was measured and a compass bearing was taken for each point. Elevations were measured with an engineer’s level, and compass bearings were taken with a staff compass.

Results and Discussion

The lowest points of fragipan expression (Fig. 2) were at an elevation of 996 ft on the south and 975 ft on the north. On the east the elevation at the point of fragipan termination was 985 ft and on the west it was at 980 ft. The pan is believed to be present throughout the entire area within the designated fragipan boundary.

As the map indicates, the pan was largely confined to the nearly level to gently sloping ridgetop. The pan was found throughout the area at a depth of 48-60 cm beneath the surface. The fragipan could be visualized as a 'blanket' draped over the flatter part of a dome.

Perhaps one reason the fragipan does not occur further down the slope is related to erosion of loessial deposits. As was suggested earlier (Zachary and Ulrich 1965, Yassoglou 1959), a relationship apparently exists between the deposition of loess and fragipan formation. At the time of loess deposition, the site was probably much the same as it is now in terms of degree of slope and general erosional characteristics. Loessial deposits were more likely to erode on the landscape areas of greatest slope. The nearly flat to gently sloping ridgetop provided an area of relative stability for the loess to accumulate, and hence a favorable environment for fragipan formation.

PHYSICAL AND CHEMICAL PROPERTIES

If plant growth is to be better understood, some knowledge of the chemical and physical properties of the soil in which plants are growing is needed. This part of the study was intended to provide that information for the site studied.

Literature Review

Grossman and Carlisle (1969) list several chemical characteristics of fragipans: (1) low organic matter, (2) low or moderate levels of extractable iron, (3) seldom calcareous, (4) few soluble salts, (5) low exchangeable-sodium levels, (6) varying exchange capacities, (7) varying base saturations, and (8) pH values ranging from 4 to 7. In Missouri, fragipans are acid (pH values of 5 and less) with other values concordant with acidic soil conditions.

Bulk density values for fragipan horizons are frequently much 3 higher than values for overlying horizons. Values from 1.5 g/cm (Franzemeir et al. 1973) to 2.1 g/cm (Knox 1957) have been reported for fragipan layers. In Missouri, Edmonds (1976), McNabb (1972), and Scrivner (1960) report bulk density for fragic horizons as 1.9, 1.7, and 1.9 respectively.

The texture of fragipans is described as loamy, or occasionally as sandy by the Soil Survey Staff (1975). However, Grossman and Carlisle (1969) indicate some fragipans may have a clay content of sixty percent but most are thought to not exceed 35 percent. Most of the fragipans reported for Missouri fall in the latter category.

Basic Question

Does the study site have significant differences in soil physical and chemical properties and, if so, how do these differences relate to the presence or absence of the fragipan?

Methods and Materials

Soil samples for chemical and physical analyses were collected from the pit face nearest the base of each tree. Samples were taken at 10 cm intervals from the surface to the bottom of each pit.

Bulk density samples were taken from the same pit face as were the other samples whenever possible. However, at times a large amount of roots and rock made it impossible to collect a satisfactory bulk density sample from this area. When this was the case, samples were taken as near as possible to the original sampling site but on the opposite pit wall.

Chemical analyses of the samples for pHw, pHs, percentage organic matter, Neutralizable acidity, phosphorous, calcium, magnesium, potassium, and sodium were done by the University of Missouri-Columbia Soil Testing Laboratory. Tests for total nitrogen were done by the University of Missouri-Columbia Agriculture Experiment Station Laboratory. Tests for NH_4OAC-extractable A and Mn were done by the author. The procedure followed was that outlined by McLean (1965). Concentrations of Al and Mn were determined by flame emission.

Bulk density was determined from soil cores or by the paraffin method which was used when the soil was too dense or too rocky to permit use of the corer. At least three independent samples were taken for each 10 cm depth. Particles less than 2mm in size were separated from each bulk density sample by the procedure outlined by Doll

(1976). The bulk density values reported are for particles less than 2 mm in size.

Particle size analyses were made with a Buoyoucous hydrometer. One hydrometer reading was taken at eight hours, which was considered to be representative of the clay-sized fraction. The suspension was then poured into a Number 270 sieve (.053 mm mesh) and washed. The residual sand was ovendried for 24 hours, weighed and then further fractionated into 2-1mm, 1-.5 mm, .5-.25 mm, .25-.106 mm, and .106-.053 mm sand classes. Total percentage sand and total percentage day were then added and the sum was subtracted from 100 to give percentage silt. All samples were analyzed in duplicate; if clay values varied more than six percent, a third sample was analyzed. The particle size data presented are an average of all samples from each 10 cm depth.

Percentage rock by volume was determined by extracting the greater than 2 mm size materials from the root sample cores (see chapter on rooting patterns for a more detailed explanation) and measuring their volume by water displacement.

All physical and chemical data are reported for 10 cm intervals (Appendices B and D) and by 30 cm intervals (Tables 2 and 3). A one-way analysis of variance (ANOVA) and a subsequent least significance difference (LSD) test were performed on data representative of each 30 cm of depth with the help of a Statistical Analysis System (SAS) computer program. Depths were labeled A (0-30 cm), B (30-60 cm), C (60-90 cm), D (90-120 cm), and E (120+ cm). Results of the tests for significance are given in Tables 2 and 3. The letters in the lower right hand corner indicate significant differences between depths for a given pit and the letters in the upper lefthand corner indicate significance between pits at the same depth. Means not sharing a letter in common differ significantly at the 0.05 level using the LSD Test.

In addition, every measured variable was plotted by depths for each profile. Those relationships that appeared to

follow a reasonably uniform pattern for several profiles are discussed below and are presented graphically.

Results and Discussion

The chemical values presented are typical of many forested, highly weathered soils in the Missouri Ozarks. Values for pHw are indicative of the acidic nature of the soil. Values for all profiles were approximately 5 in the surface 30 cm of soil and decreased with depth to values of 4.7-4.3 for the 120+ depth (Table 3). Organic matter was low and decreased with depth. All values were less than 2 percent (Table 3).

Table 2. Physical data by 30cm depths for the seven profile.

Tree Species, Pit Number, and % Sand

Depth	Variable	Black Oak	Black-Jack Oak	Black Oak	Black-Jack Oak	Black Oak	Black Oak	Post Oak
		One	Three	Four	Five	Six	Seven	Eight
A	% sand	b 16.140 b	a 6.090a	a 5.437a b	a 4.843ab	a 5.607a	b 12.180a	b 12.947b
B	% sand	D 12.650 ab	Bcd 9.900bc	ab 6.243a	ab 6.037b	abc 7.423a	cd 1.867bc	a 4.957a
C	% sand	bc 7.213a	C 10.767c	ab 4.343a	a 2.097a	bc 7.930a	ab 6.013a	a 2.107a
D	% sand	C 17.117 b	Ab6. 6.713ab	ab 5.140a	a 2.447a	ab 5.223a	b 7.440ab	ab 4.690a
E	% sand	c 10.720 ab		abc 6.290a	a 2.350a	ab 5.565a	ab 5.000a	bc 7.420ab

Table 2. (continued).

Tree Species, Pit Number, and % Silt

Depth	Variable	Black Oak	Black-Jack Oak	Black Oak	Black-Jack Oak	Black Oak	Black Oak	Post Oak
		One	Three	Four	Five	Six	Seven	Eight
A	% silt	ab 55.010c	a 54.750b	ab 60.217b	b 64.697b	b 74.220c	ab 68.687c	ab 63.923c
B	% silt	a 16.697b	b 57.080b	b 53.567b	b 49.633b	b 50.727b	b 56.133c	b 43.207b
C	% silt	a 3.690a	ab 10.227a	b 27.253a	ab 17.870a	c 49.027b	c 55.093c	ab 9.673a
D	% silt	a 4.527a	ab 10.877a	ab 8.810a	ab 8.903a	ab 10.217a	c 31.143b	b 14.593a
E	% silt	a 7.830ab		a 4.210a	a 11.000a	a 8.470a	a 12.470a	b 21.713a

Table 2. (continued).

Tree Species, Pit Number, and % Clay

Depth	Variable	Black Oak	Black-Jack Oak	Black Oak	Black-Jack Oak	Black Oak	Black Oak	Post Oak
		One	Three	Four	Five	Six	Seven	Eight
A	% clay	a 28.850a	a 39.150a	a 34.347a	a 30.460a	a 20.173a	a 19.133a	a 23.130a
B	% clay	c 70.653b	a 33.020a	ab 40.190a	ab 44.300a	ab 41.860b	a 32.000b	b 51.837b
C	% clay	b 89.097c	b 78.957b	b 68.403b	b 80.033b	a 43.043b	a 38.893b	b 88.220c
D	% clay	78.357bc	bc 82.410b	bc 86.050b	d 88.650b	bc 84.660c	a 61.417c	bc 80.717c
E	% clay	ab 81.950bc		b 89.500b	ab 80.650b	b 85.965c	b 82.260c	a 70.866bc

Table 2. (continued).

Tree Species, Pit Number, and Bulk Density

Depth	Variable	Black Oak	Black-Jack Oak	Black Oak	Black-Jack Oak	Black Oak	Black Oak	Post Oak
		One	Three	Four	Five	Six	Seven	Eight
A	BD	b 1.463a	b 1.450b	b 1.423ab	ab 1.393ab	a 1.327a	ab 1.400a	ab 1.390b
B	BD	a 1.453a	a 1.450b	ab 1.513ab	b 1.737c	a 1.453b	ab 1.573a	a 1.383b
C	BD	ab 1.367a	ab 1.363ab	c 1.670b	bc 1.570bc	c 1.730c	c 1.670a	a 1.263a
D	BD	a 1.383a	a 1.347a	bc 1.470ab	a 1.303a	a 1.347a	c 1.610a	a 1.283a
E	BD	bc 1.335a	abc 1.290a	c 1.365a	bc 1.335a	ab 1.225a	c 1.355a	a 1.245a

Table 2. (continued).

Tree Species, Pit Number, and % Rock

Depth	Variable	Black Oak	Black-Jack Oak	Black Oak	Black-Jack Oak	Black Oak	Black Oak	Post Oak
		One	Three	Four	Five	Six	Seven	Eight
A	% rock	a 6.667a	a 5.00a	a 2.333a	a 1.667a	a 3.000a	a 7.000ab	b 17.333b
B	% rock	a 2.000a	ab 11.000b	ab 11.333a	ab 8.667a	ab 10.000ab	b 16.000c	ab 8.333a
C	% rock	a 1.333a	a 4.000a	b 31.667b	a 6.333a	a 12.333b	a 5.000a	a 6.333a
D	% rock	c 13.333b	a 0.667a		ab 4.667a	ab 5.667ab	bc 10.333abc	bc 9.000a
E	% rock	27.500c	6.000a		5.500a	2.667a	11.750bc	27.000b

Table 3. Chemical soil data by 30 cm depths for the seven profiles.

Pit Number, Depth, and pH_s

Depth	Variable	One	Three	Four	Five	Six	Seven	Eight
A	pH_s	b 4.133a	ab 4.033a	b 4.133b	a 3.900a	ab 4.033b	b 4.067b	b 4.133c
B	pH_s	c 4.067	c 4.100a	ab 3.900a	a 3.833a	a 3.867a	bc 4.000b	c 4.067c
C	pH_s	c 4.067a	c 4.067a	ab 3.967a	a 3.900a	a 3.900a	ab 3.967a	bc 4.033bc
D	pH_s	ab 3.933a	b 4.000a	ab 3.933a	a 3.867a	ab 3.933a	b 4.033b	a 3.900b
E	pH_s	c 4.050b		bc 3.900a	abc 3.900a	ab 3.850a	ab 3.850a	a 3.733a

Table 3. (continued).

Pit Number, Depth, and % Organic Matter

Depth	Variable	One	Three	Four	Five	Six	Seven	Eight
A	% OM	ab 1.533b	ab 1.333b	b 1.833b	a 0.900a	ab 1.333ab	b 0.833c	ab 1.700a
B	% OM	a 0.733ab	ab 1.033b	ab 1.000a	ab 0.767a	ab 1.000ab	b 1.367ab	b 1.333c
C	% OM	a 0.533a	a 0.633a	b 1.933b	a 0.733a	b 1.767b	b 1.767bc	a 0.600a
D	% OM	abc 0.667a	ab 0.633a	a 0.400a	bcd 0.767a	cd 0.967ab	c 1.033a	bcd 0.833ab
E	% OM	b 0.950ab		a 0.350a	b 1.000a	b 0.750a	b 0.850a	c 1.300bc

Table 3. (continued).

Pit Number, Depth, and pH_w

Depth	Variable	One	Three	Four	Five	Six	Seven	Eight
A	pH_w	b 5.000a	ab 4.767a	b 4.933b	ab 4.767b	b 4.900c	a 4.633a	ab 4.833c
B	pH_w	d 5.000a	cd 4.933a	bc 4.800ab	a 4.567ab	ab 4.633b	ab 4.633a	bc 4.800bc
C	pH_w	c 4.833b	c 4.800a	a 4.833ab	a 4.333a	bc 4.733bc	b 4.667a	c 4.867c
D	pH_w	bc 4.733b	bc 4.767a	c 4.833ab	a 4.33a	b 4.600b	c 4.800a	bc 4.667b
E	pH_w	b 4.700b		b 4.700a	a 4.400a	a 4.350a	b 4.700a	a 4.333a

Table 3. (continued).

Pit Number, Depth, and K (meq/100g)

Depth	Variable	One	Three	Four	Five	Six	Seven	Eight
A	(meq/100g) K	a 0.120a	bcd 0.211a	d 0.237ab	abc 0.158a	ab 0.137a	d 0.237b	cd 0.231a
B	K	ab 0.186b	a 0.149a	bc 0.216a	bc 0.233b	d 0.282c	cd 0.260b	bcd 0.224a
C	K	bc 0.224b	ab 0.182a	ab 0.190a	d 0.301b	ab 0.209b	a 0.175a	cd 0.261a
D	K	a 0.201b	a 0.210a	a 0.196a	c 0.406c	b 0.271c	a 0.179a	a 0.267a
E	K	a 0.215c		b 0.292b	d 0.410c	c 0.375d	ab 0.234b	ab 0.241a

Table 3. (continued).

Pit Number, Depth, and N

Depth	Variable	One	Three	Four	Five	Six	Seven	Eight
A	N	ab 0.039a	ab 0.054b	ab 0.051d	ab 0.047a	ab 0.050ab	a 0.034bc	b 0.061a
B	N	ab 0.042a	a 0.030a	ab 0.043c	ab 0.046a	b 0.071b	ab 0.038c	ab 0.039ab
C	N	d 0.035b	ab 0.026a	bc 0.030b	a 0.025a	a 0.024ab	a 0.023a	cd 0.032a
D	N	ab 0.024bc	ab 0.026a	ab 0.024a	b 0.039a	ab 0.022a	ab 0.021a	ab 0.026a
E	N	a 0.022c		ab 0.025ab	b 0.030a	ab 0.024ab	ab 0.024ab	a 0.022a

Table 3. (continued).

Pit Number, Depth, and P_2O_5 (lbs/ac)

Depth	Variable	One	Three	Four	Five	Six	Seven	Eight
A	(lbs/ac) P_2O_5	a 6.000c	a 5.667a	a 6.667a	b 19.667b	a 10.667b	a 5.667c	a 11.000b
B	P_2O_5	a 5.000c	a 1.000a	b 11.667a	b 11.667b	c 18.667c	a 3.000b	a 4.000a
C	P_2O_5	ab 2.000ab	a 1.000a	b 13.667	Ab 3.000a	ab 5.667ab	ab 4.000bc	ab 3.000a
D	P_2O_5	a 1.000a	a 3.000a	b 6.000a	a 3.000a	a 3.000a	a 3.000b	a 3.000a
E	P_2O_5	ab 4.500c		b 8.500a	a 0.000a	a 1.500a	a 0.000a	a 3.000a

Table 3. (continued).

Pit Number, Depth, and Ca

Depth	Variable	One	Three	Four	Five	Six	Seven	Eight
A	Ca	abc 0.375a	bc 1.583a	abc 0.900bc	a 0.592a	abc 0.908a	c 1.300a	a 0.633a
B	Ca	bc 1.158b	ab 0.833a	a 0.725ab	a 0.750a	c 1.400ab	c 1.483ab	a 0.534a
C	Ca	b 1.1225b	ab 0.800a	a 0.450a	c 2.142b	c 1.817b	b 1.183a	a 0.475ab
D	Ca	a 1.325b	a 1.000a	a 1.083c	b 3.133c	b 3.017c	a 1.450ab	a 0.925bc
E	Ca	bc 2.238c		ab 1.725d	cd 3.200c	d 3.875d	abc 1.825b	a 1.341c

Table 3. (continued).

Pit Number, Depth, and Na (meq/100g)

Depth	Variable	One	Three	Four	Five	Six	Seven	Eight
A	(meq/100g) Na	ab 0.150a	b 0.134a	b 0.123a	ab 0.105a	ab 0.105a	ab 0.102a	a 0.091
B	Na	b 0.167b	ab 0.137a	ab 0.124a	b 0.178a	b 0.167a	a 0.102a	ab 0.156a
C	Na	ab 0.229c	b 0.309b	b 0.319b	c 0.474b	b 0.322b	a 0.141a	b 0.315b
D	Na	a 0.366d	ab 0.498c	a 0.529c	b 0.608c	b 0.587c	a 0.377b	a 0.402c
E	Na	ab 0.489e		cd 0.718d	cd 0.707c	d 0.793d	bc 0.567c	a 0.446c

Table 3. (continued).

Pit Number, Depth, and % BS

Depth	Variable	One	Three	Four	Five	Six	Seven	Eight
A	% BS	ab 16.797a	abc 21.584a	abc 22.164b	a 12.836a	bc 25.367ab	c 30.376b	c 26.580b
B	% BS	c 21.369b	a 20.518a	a 19.666b	bc 18.743b	bc 22.219a	d 33.905b	ab 19.504a
C	% BS	bcde 22.496b	bc 21.776a	a 15.641a	cde 25.484c	e 27.334ab	bcd 22.030a	ab 18.655a
D	% BS	bc 24.718b	c 25.211a	a 19.521ab	d 30.488c	c 25.755ab	abc 22.441a	ab 20.669a
E	% BS	b 31.029c		a 23.475b	b 29.967c	b 31.491b	a 23.746a	a 23.214ab

Table 3. (continued).

Pit Number, Depth, and CEC (meq/100g)

Depth	Variable	One	Three	Four	Five	Six	Seven	Eight
A	(meq/100g) CEC	ab 9.940a	c 21.184ab	ab 12.105a	bc 16.823a	a 8.450a	a 7.908a	a 8.052a
B	CEC	c 23.346b	ab 16.981a	ab 17.414ab	bc 22.569b	bc 22.064	a 12.351ab	bc 20.382b
C	CEC	b 25.373b	b 25.345bc	ab 21.752bc	b 26.922	a 17.980b	a 17.317b	b 26.848c
D	CEC	ab 23.235b	cd 26.533c	bc 25.477c	cd 28.292c	d 28.904c	a 20.808b	cd 27.322c
E	CEC	A 22.446b		ab 26.472c	ab 27.130c	b 28.466c	ab 24.898b	ab 25.388bc

Table 3. (continued).

Pit Number, Depth, and NAC (meq/100g)

Depth	Variable	One	Three	Four	Five	Six	Seven	Eight
A	(meq/100g) NAC	a 8.167a	a 16.500ac	a 9.500a	bc 14.667a	ab 0.33a	c 5.500a	a 6.00a
B	NAC	c 18.333b	b 13.500a	bd 14.000ab	c 18.333ab	bc 17.167bc	a 8.167ab	bc 16.500b
C	NAC	c 19.667bc	c 19.833c	bc 18.333bc	c 20.000b	a 13.167b	ab 13.667bc	c 21.833b
D	NAC	ab 17.500bc	bc 19.667c	c 20.500c	bc 19.667b	c 21.500c	a 16.167c	c 21.667b
E	NAC	a 15.500c		b 20.250c	ab 19.000ab	b 19.500c	b 19.000c	b 19.500b

Table 3. (continued).

Pit Number, Depth, and Al (ppm)

Depth	Variable	One	Three	Four	Five	Six	Seven	Eight
A	(ppm) Al	ab 47.767a	b 78.8333a	ab 50.000a	b 78.333a	a 33.833a	a 34.500a	a 34.833a
B	Al	bc 104.833c	a 62.667a	bc 77.833ab	c 118.833a	abc 85.167b	a 60.500b	bc 113.167bc
C	Al	ab 109.333c	ab 98.333a	ab 100.500b	bc 116.000a	ab 80.667b	a 74.333b	c 145.167bc
D	Al	a 76.333b	abc 98.667a	c 104.833b	abc 88.833a	bc 99.500b	ab 77.833bc	d 147.833c
E	Al	a 48.500ab		bc 87.750ab	ab 69.500a	bc 84.750b	c 102.500c	c 104.000b

Table 3. (continued).

Pit Number, Depth, and Mn (ppm)

Depth	Variable	One	Three	Four	Five	Six	Seven	Eight
A	(ppm) Mn	a 2.747a	a 1.902b	a 2.933b	a 2.058b	a 5.092b	a 5.955b	a 0.096a
B	Mn	a 0.233a	a 0.276a	a 0.347a	ab 0.558ab	b 0.813a	ab 0.535a	a 0.268a
C	Mn	abc 0.202a	a 0.127a	ab 0.155a	ab 0.163a	bc 0.258a	c 0.289a	ab 0.185a
D	Mn	a 0.125a	ab 0.208a	a 0.150a	b 0.247ab	ab 0.205a	ab 0.185a	a 0.142a
E	Mn	a 0.173a		a 0.158a	a 0.125ab	a 0.235a	a 0.178a	a 0.192a

Table 3. (continued).

Pit Number, Depth, and Mg (meq/100g)

Depth	Variable	One	Three	Four	Five	Six	Seven	Eight
A	(meq/100g) Mg	ab 1.174a	b 2.755a	ab 1.344a	ab 1.301a	a 0.967a	a 0.769a	ab 1.186a
B	Mg	b 3.502b	a 2.361a	a 2.349ab	ab 3.075b	ab 3.049b	a 2.339b	b 3.570b
C	Mg	b 4.028b	b 4.221ab	a 2.460b	b 4.004bc	a 2.465b	a 2.150b	b 3.964b
D	Mg	c 3.843b	a 4.957b	a 3.068b	b 4.478c	b 3.529c	a 2.636bc	a 4.061b
E	Mg	b 4.005b		a 3.488b	b 3.813bc	b 3.923c	b 3.263c	b 3.875b

Note: Letters in the upper lefthand corner indicate significant differences between pits at the same depth. Letters in the lower righthand corner indicate significant differences between depths within the same pit. Means not sharing a letter in common differ significantly at the 0.05 level by the LSD Test.

Sodium

Sodium content was related to soil depth in all profiles (Fig. 4). Generally, sodium values were in the 10 meq/l00g range for the 5-45 cm depth, increased at 55 cm, and continued to increase with depth. The values for sodium for the 5-45 cm depths are from the soil derived from the loess while the values for depths greater than 55 cm are from the sandstone derived soil.

Magnesium

Profiles 1 and 8 had the same general pattern (Fig. 5) with values being near 0 at the 5 cm level. Magnesium levels increased with depth in the profile to approximately 45 cm. From approximately 45 cm to 140 cm values for Mg were between 3.5 and 4.5 meq/100g. The two different parent materials are probably responsible for this pattern as well as the lack of fragic characteristics. Profiles 3,4,5,6, and 7 were generally similar in that there was an initial increase from approximately 0 to 3.5 meq/100g with depth in the profile followed by a pronounced decrease in concentration at about 55 cm to approximately 2.0. Below this depth magnesium concentrations increased with depth. The decrease in Mg in the 55 cm zone may be the result of the highly leached condition associated with a fragipan.

Cation Exchange Capacity

The general relationship of CEC to depth (Fig. 6) is similar to that of Mg. The reason for this is thought to be the same as that offered for Mg.

Neutralizable Acidity

The relationship between NAC and depth was not as clearly defined as that of Mg and CEC to depth. Nevertheless, the general pattern (Fig. 7) appears similar to that of Mg and CEC.

Manganese

In all profiles, more Mn was present in the upper 35 cm (values ranged between 3 and 24 ppm) than in the depths greater than 35 cm. Below the 35 cm depth values for Mn were less than 2 ppm (Fig. 8).

Aluminum

Concentrations of Al tended to be lower in the surface 30 cm of soil, where the amount of Al varied from 35 to 80 ppm, than in the lower depths (Table 3). Greatest concentrations of Al were present in the 30-120 cm interval zone. Concentrations in this zone were between 60 and 120 ppm.

Figure 4. Sodium concentration in the seven profiles by depth.

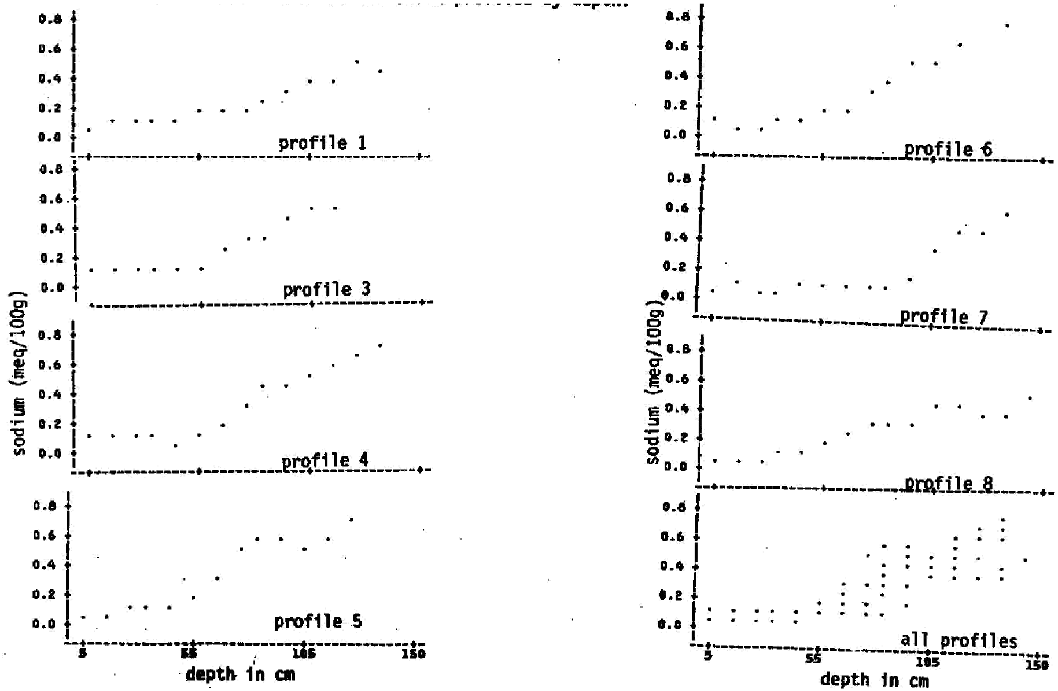


Figure 5. Magnesium concentration in the seven profiles by depth.

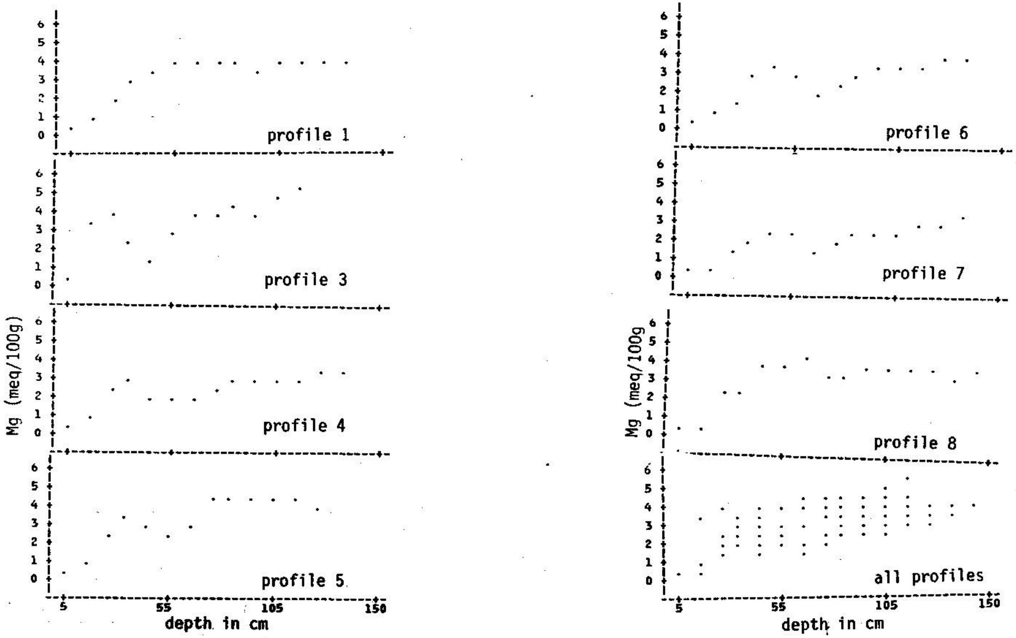


Figure 6. Cation exchange capacity values by depth for the seven profiles.

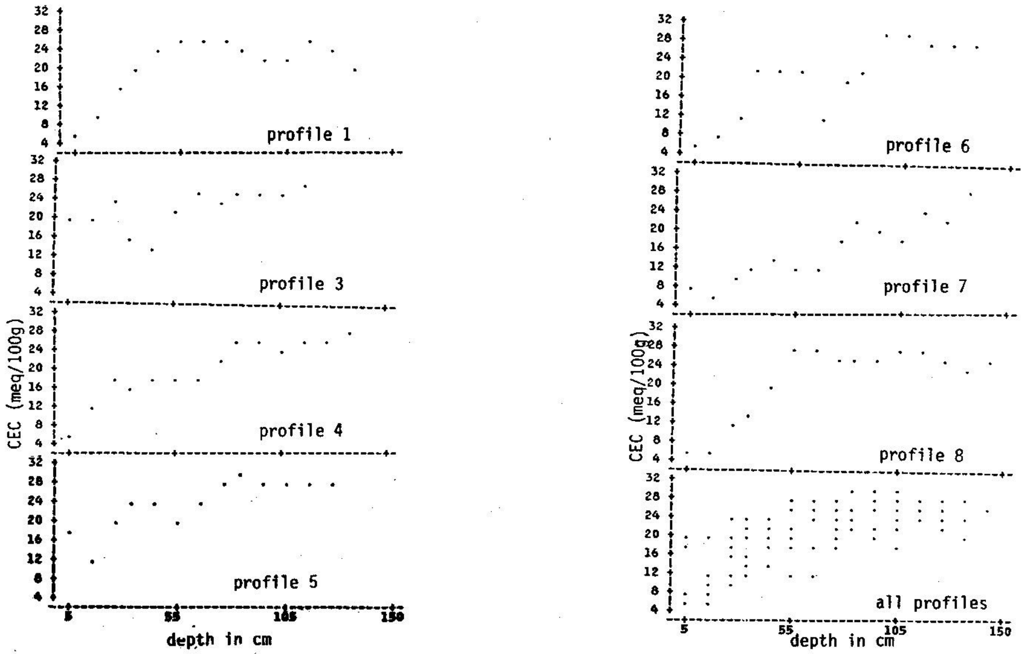


Figure 7. Neutralizable acidity values by depth for the seven profiles.

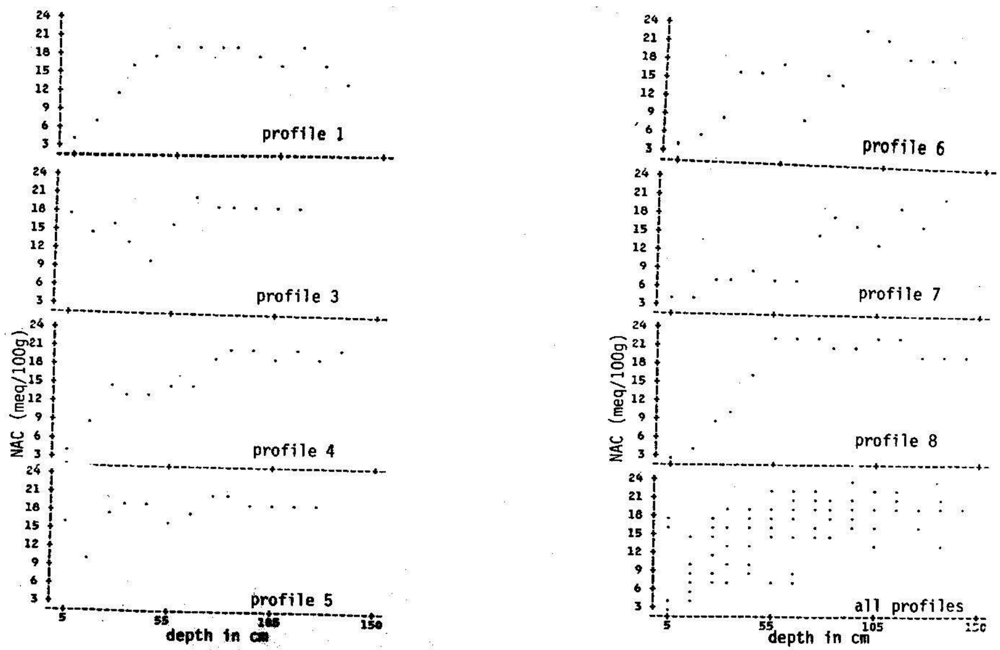
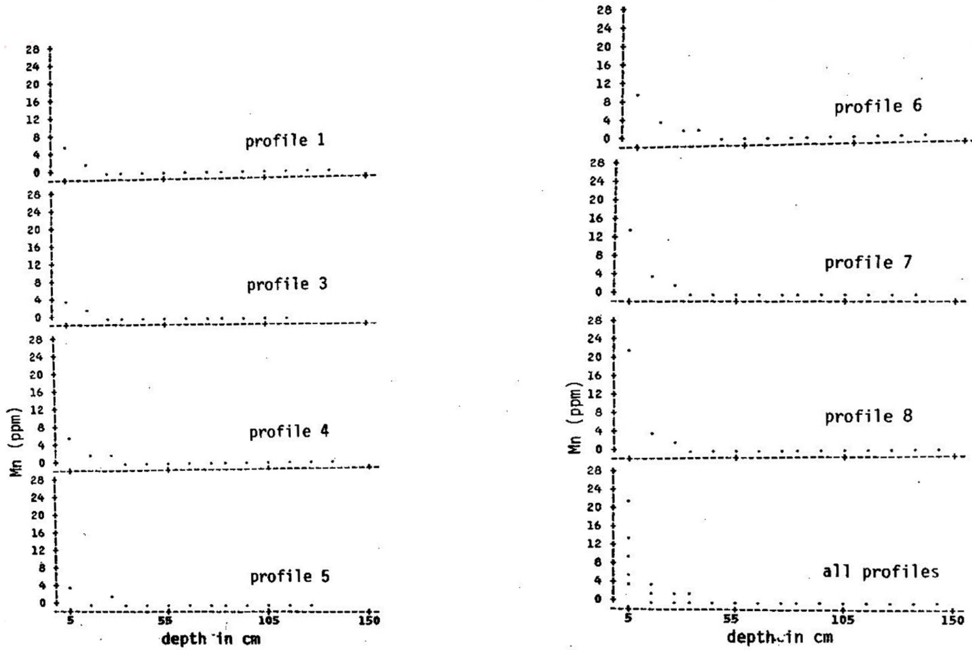


Figure 8. Manganese concentration by depth for the seven profiles.



Base Saturation

There was little variation in base saturation with depth within profiles and between profiles at the same depth (Table 3). Values ranged from approximately 13 percent to 34 percent.

Total Nitrogen

Values for total nitrogen were low. There was a pattern of decreasing amounts with increasing depths—.034-.061 percent at depth A to .022-.030 percent for depth E (Table 3).

Phosphorus

Values for phosphorus were very low, ranging from 0 lbs of P_2O_5/acre to 19 lbs of P_2O_5/acre (Table 3).

Potassium

Potassium values were low, ranging from approximately .1 to .3 (meq/100g). Values tended to decrease with depth in the profile (Table 3).

Bulk Density

The relationship of bulk density to depth was much the same for profiles 1 and 8 (Figs. 9 and 15). Values were between 1.5 – 1.3 g/cm^3 for all depths sampled. Profiles 3,4,5,6, and 7 (Figs. 10-14) had much higher BD values (above 1.6 g/cm^3). In those profiles, values for bulk density tended to increase above 1.5 g/cm^3 at about the 60 cm depth. Values were generally between 1.85 and 1.6

g/cm^3 for the 60-100 cm depth and then decreased to 1.4 g/cm^3 or less.

Particle Size Analysis

Particle size distributions for profiles 1 and 8 (Figs. 9 and 15) were alike. In the upper 10 cmof soil, clay content was low (less than 20 percent) and silt was high (approximately 70 percent). As depth increased, however, clay became the dominant particle size. Clay content increased in both profiles to approximately 80 percent at 70 cm and remained near that value throughout the lower depths of the profile.

Figure 9. PROFILE 1

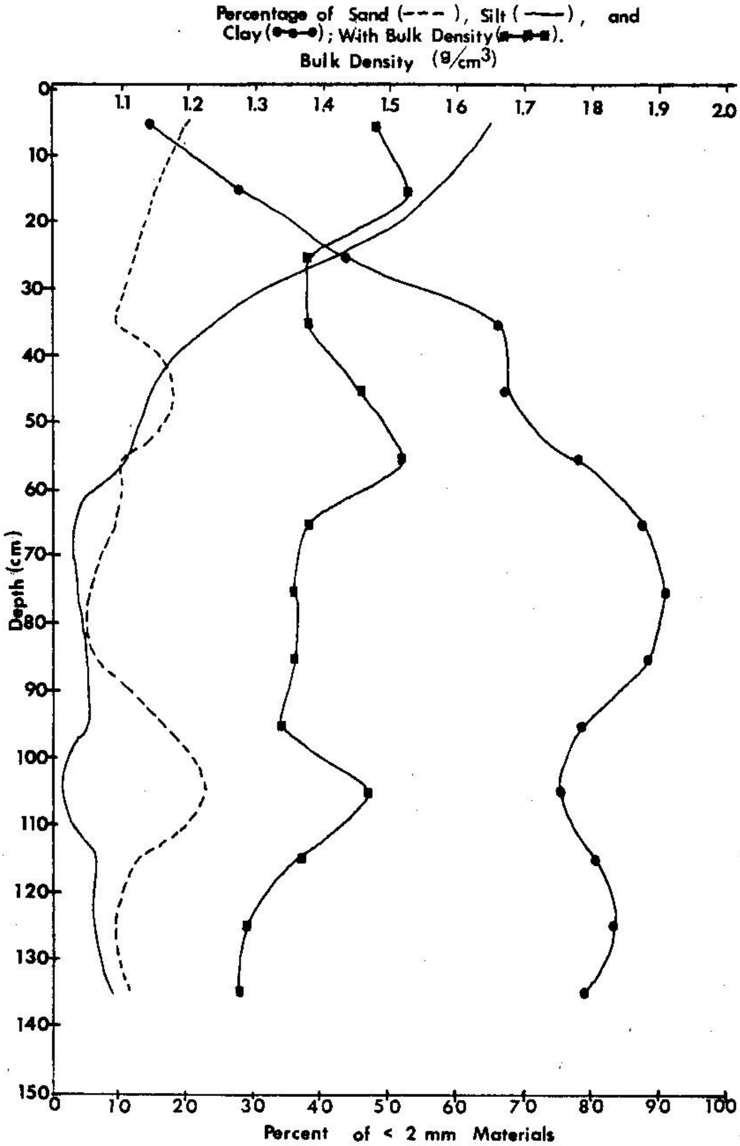


Figure 10. PROFILE 3

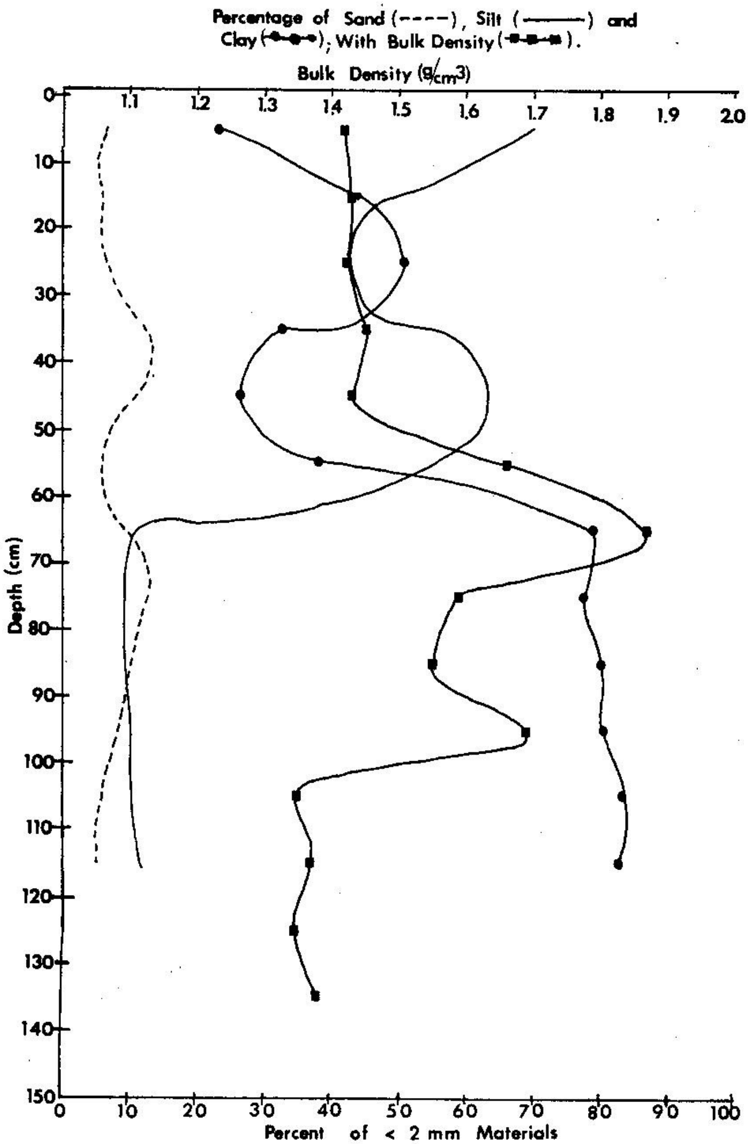


Figure 11. PROFILE 4

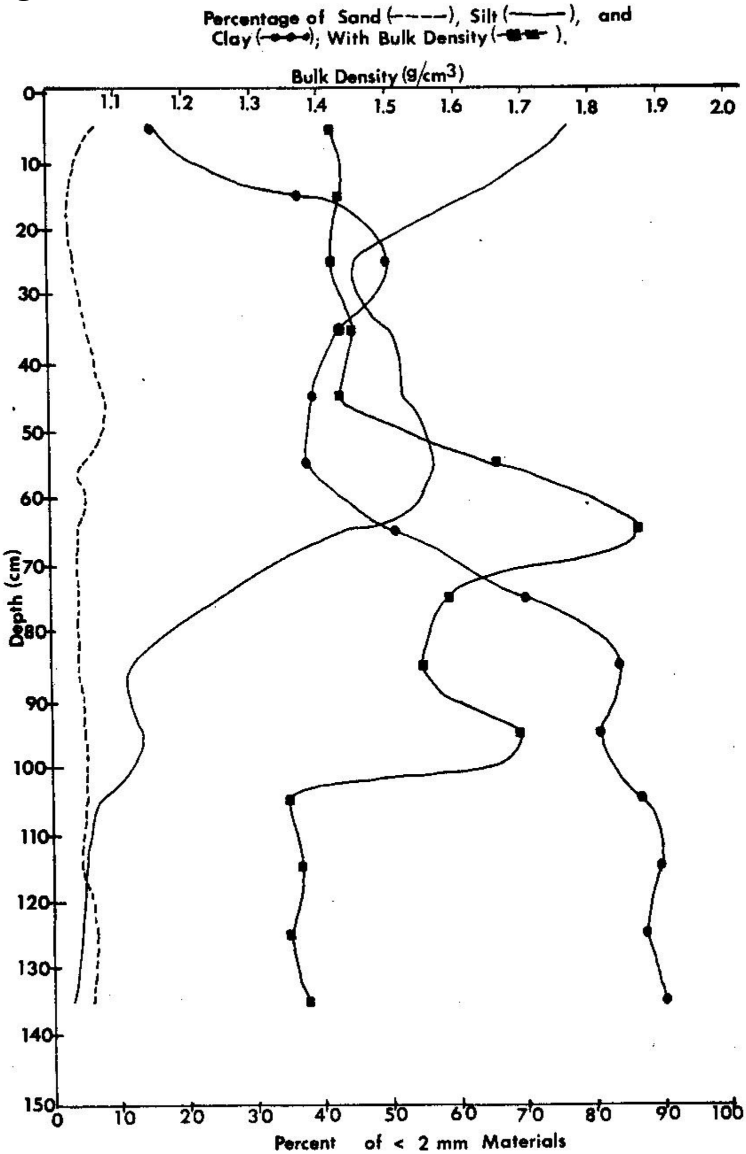


Figure 12. PROFILE 5

Percentage of Sand (----), Silt (———), and Clay (-●-●-●); With Bulk Density (-■-■-).

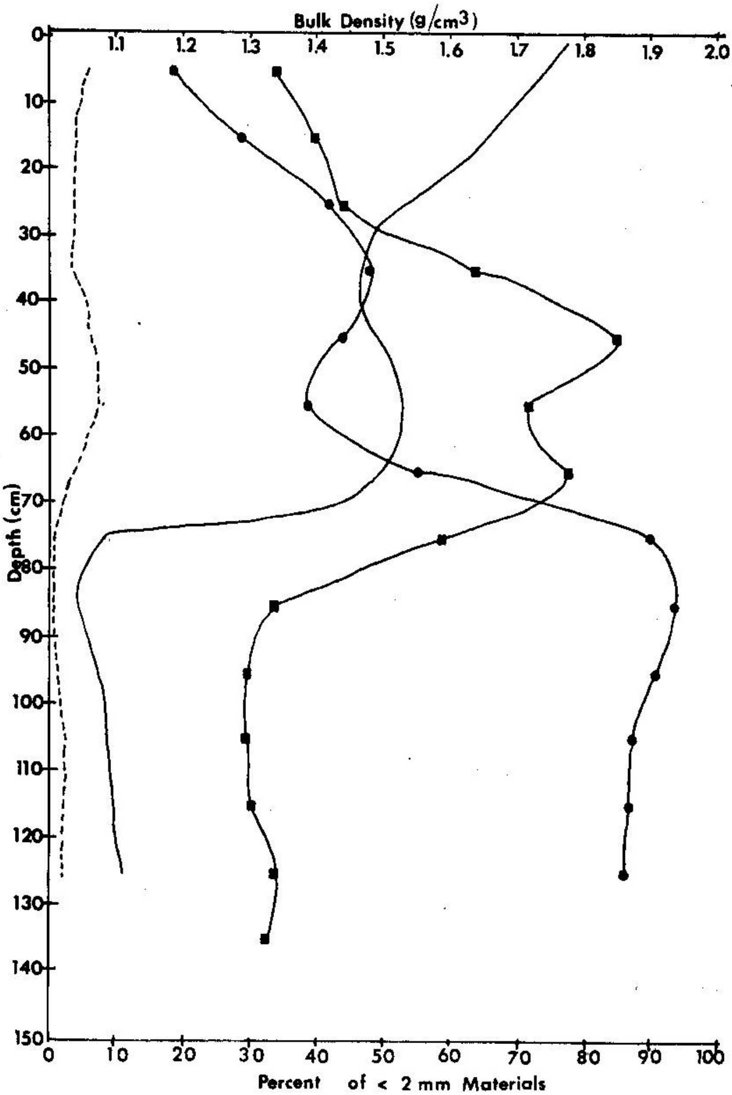


Figure 13. PROFILE 6

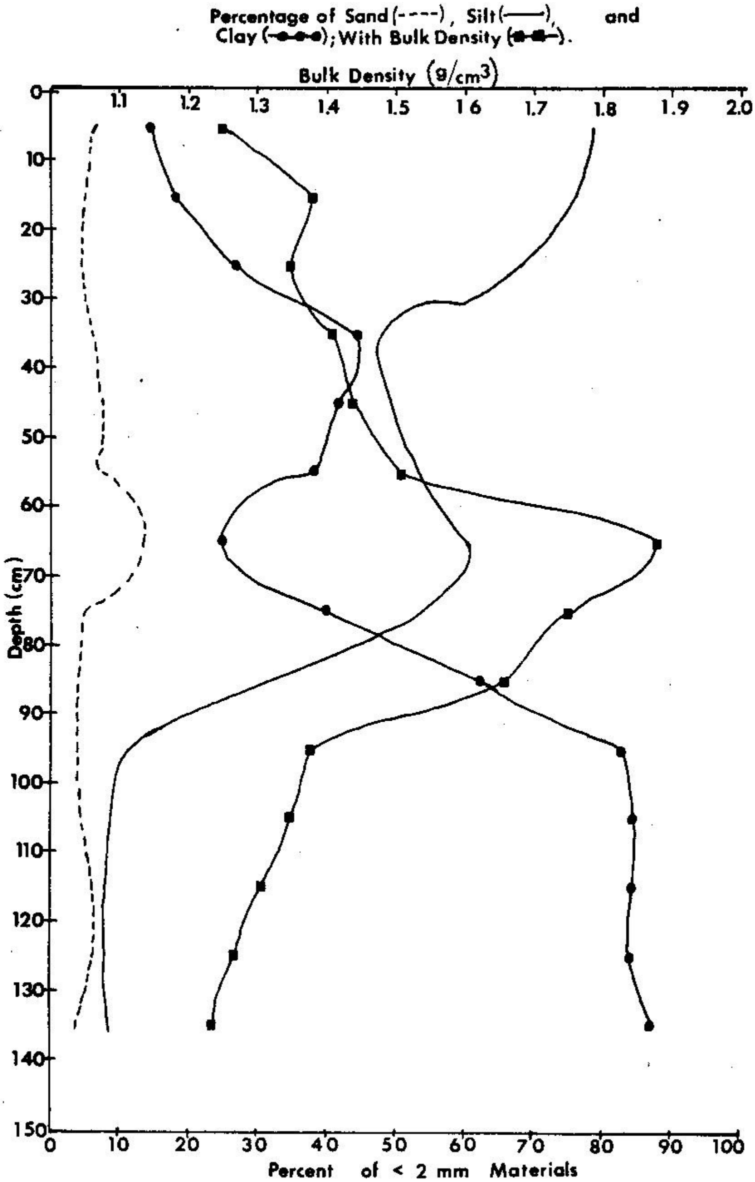


Figure 14. PROFILE 7

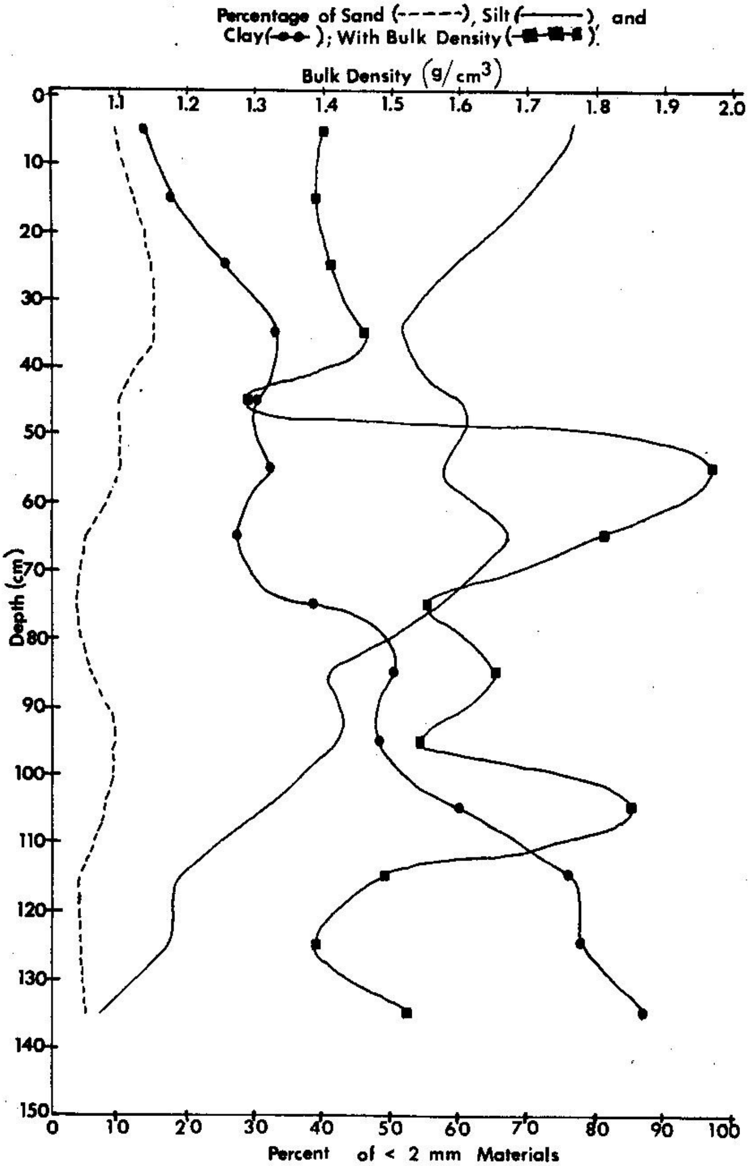
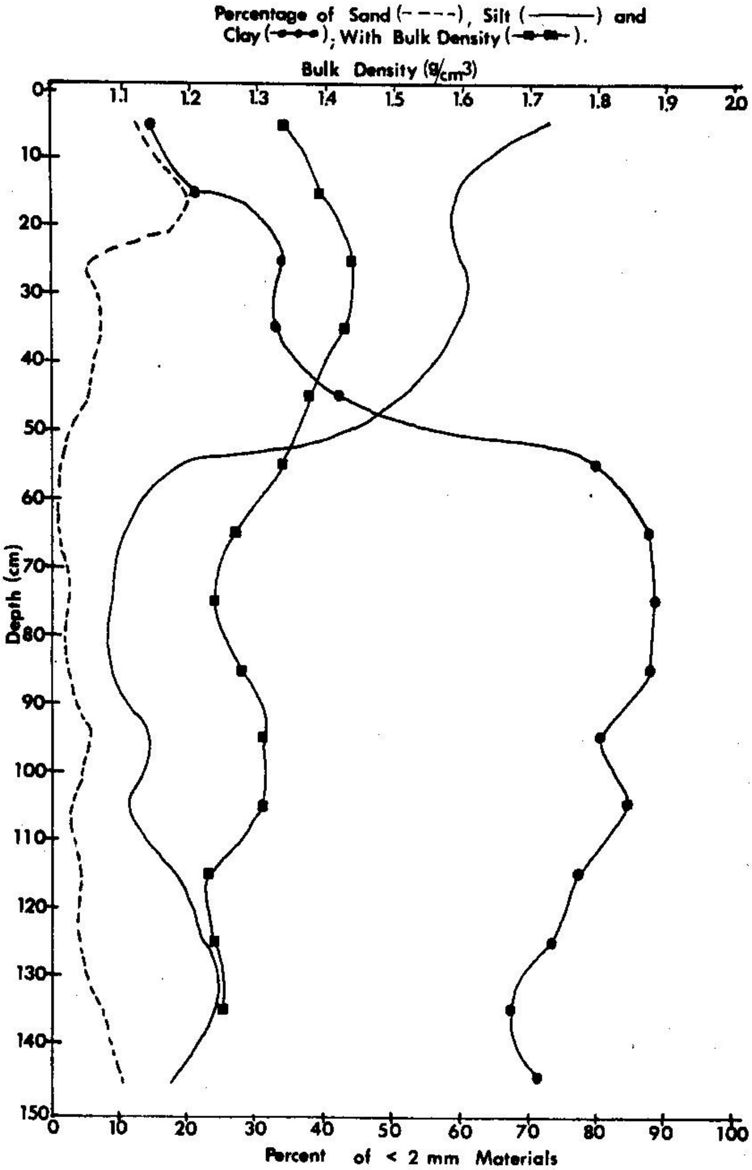


Figure 15. PROFILE 8



Profiles 3 through 7 (Figs. 10-14) had particle size distribution patterns somewhat like profiles 1 and 8, but tended to decrease in clay content to approximately 10 percent in the 30-60 cm zone.

Degree of fragipan expression varied between being well-expressed and not well-expressed depending on location within pits 3,4,5,6, and 7. Data from particle size analyses of peds of a well-expressed fragic nature (Fig. 16 and Tables 4 and 5) from pits 4,5,6, and 7 indicate that the well-developed fragipan on this site had a clay content of less than 35 percent. Therefore, it seems that within the soil sampled (the pit face 1 m from the base of each tree) for profiles 3 through 7 an incipient fragipan was present. The general nature of the definition of the term prevents a conclusive answer. In the following chapter on rooting patterns I offer an explanation as to why the fragipan is not well-expressed in the soil 1 m distant from the base of each tree.

In summary: (1) Bulk density values were higher in profiles 3 through 7 than bulk density values observed in either profiles 1 or 8. (2) A fragipan was not present in profiles 1 and 8. A fragipan was present in pits 3 through 7 but was not well expressed in the profiles sampled. (3) There were few differences in chemical properties between fragipan profiles and non-fragipan profiles.

Figure 16. Photographs of fragic peds.

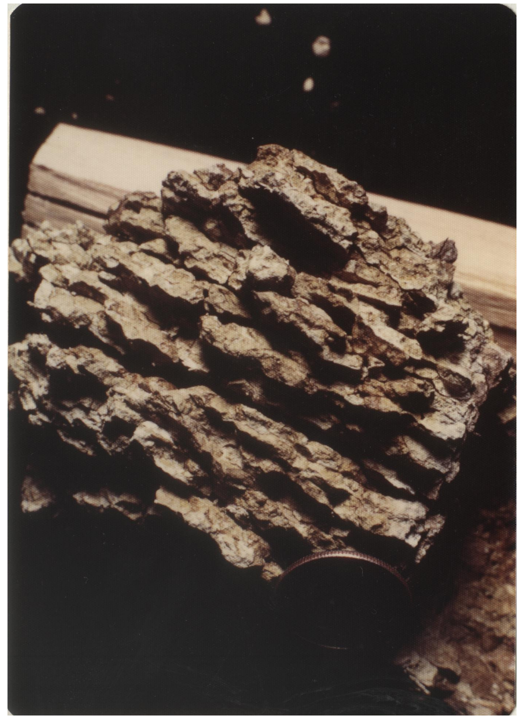


Table 4. Particle size analysis of strongly expressed fragic peds.

Percent of 2mm Materials

Pit No.	**2-1 mm**	**1-.5 mm**	**.5-.25 mm**	**.25-.10 mm**	**.10-.05 mm**	**Total Sand**	**Silt .05-.002**	**Clay .002 mm**
4	1.92	0.60	0.83	1.59	1.33	5.64	60.36	34.00
5	5.23	2.05	2.62	2.90	0.84	13.64	60.76	25.60
6	1.72	0.61	0.80	1.11	0.78	5.02	63.58	31.40
7	3.87	1.71	2.03	2.09	0.83	10.59	56.47	33.00

Table 5. Particle size class name for the strongly expressed fragic peds.

Pit Number	Class Name
4	Silty clay loam
5	Silt loam
6	Silty clay loam
7	Silty clay loam

ROOTING PATTERNS

The importance of rooting depth to tree growth underscores the need for better understanding of the extent fragipan horizons restrict root growth. Consequently, differences in rooting patterns of oak trees growing on soils with a fragipan and oak trees growing on soil without a fragipan were examined.

Literature Review

The literature contains a number of references to the restrictive nature of fragipans on root growth (F1 etcher and McDermott 1957, Arnold 1975, Carlisle et al. 1957, Miller et al. 1971, Fritton and Olson 1972, Soil Survey Staff 1975). All point to little penetration of the pan by roots except for some root growth in the cracks between the peds. However, McNabb (1972) and McNabb and Cox (1973, 1976) in their study of oak growing on a well-expressed fragipan in southeastern Missouri concluded a reduction of root length in the fragipan horizons as compared to the immediate overlying horizons was not apparent. The seasonal watertable present above the fragipan until early summer was considered to reduce root numbers and length in the saturated zone.

Millet and Collins (1967), who studied the Lebanon, Plato, and Hobson soils in Missouri, reported fragipans shallower than 61 cm seriously affected height and root growth, whereas fragipans deeper than 61 cm had very little effect on height growth and the rooting habits of trees. In a study of slash pine growing in a southeast Texas soil with a fragipan, Batte (1975) and Batte and Moehring (1976) observed very few roots penetrating the brittle fragipan matrix. They concluded depth to the pan and pan continuity were major factors influencing rooting patterns in the soil.

Basic Question

Are there significant differences in the root distribution patterns of trees growing on soils with a fragipan as opposed to those growing on soils without a fragipan?

Methods and Materials

Roots were sampled at a distance of 1 m from each tree with a hand driven soil sampler (Fig. 17) patterned after the one described by Jurgensen (1977). The length of the sampler was 45 cm and the diameter of the cutting edge was 10 cm. Two sets of root samples were taken at each tree. Each set of samples was taken to a depth of at least 120 cm unless rock was encountered that the sampler could not be driven through (as was the case at profile 4 at a depth of 90 cm). The procedure used was to pound the soil sampler into the ground with the sliding hammer to a depth of about 30 cm, give the sampler a half-turn by beating on one of the handles, and then extract the sampler by prying under one of the handles with a long metal bar. After the second core sample was taken, the soil surrounding the hole was removed to a depth equal to the length of the two cores just extracted. After the cores containing soil, rock, and roots were pushed from the sampler (oil was used to lubricate the inside of the sampler prior to each sampling), the cores were wrapped in clear plastic film, and placed in sections of split plastic pipe 36 cm long and 10 cm in diameter. The protected cores were transported to the Forest Ecology Laboratory in Columbia to await measurement.

The original plan had been to take the root samples in the same immediate area from which the samples for soil physical and chemical analysis had been taken and where the soil description had been made. However, the force needed to drive the sampler into the soil caused that face of the pit to crumble. Consequently, the samples were taken

approximately 50 cm from the edge of the pit and at a distance of 1 m from the base of the tree whose roots were being measured (Fig. 18).

Root length and weight were measured. Root length was measured for each 10 cm length of soil core with an instrument built by John Roberts (Senior Research Analyst, School of Forestry, Fisheries and Wildlife, University of Missouri-Columbia).

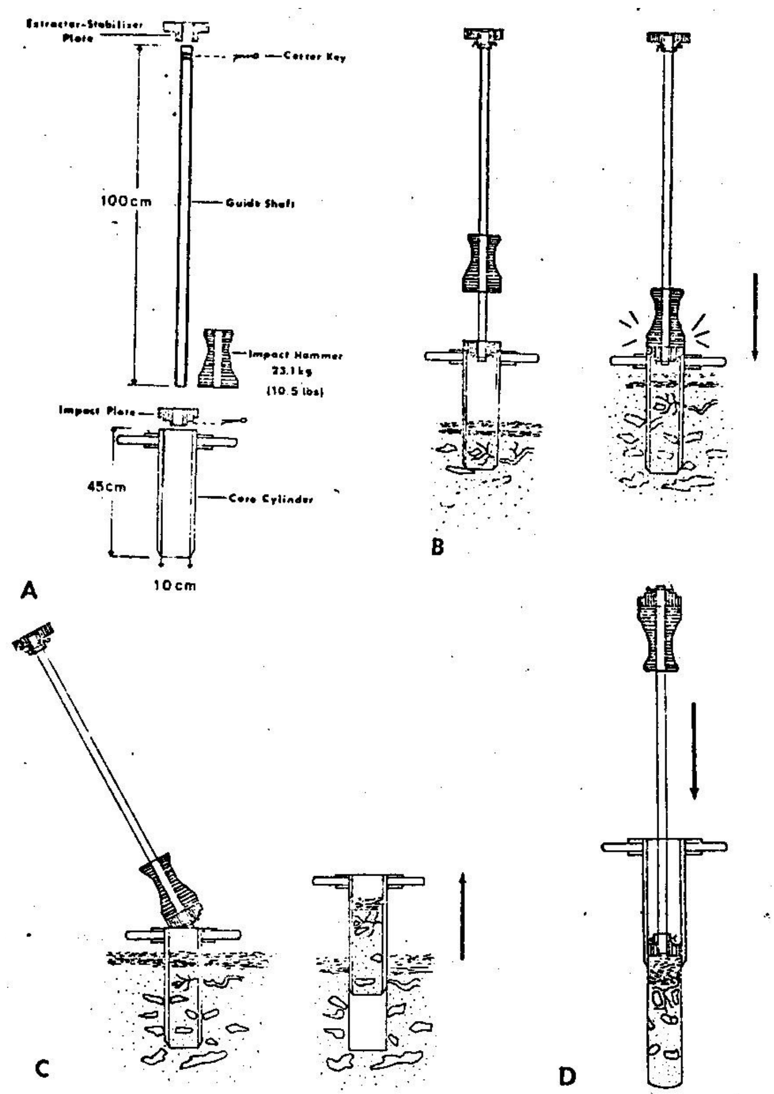
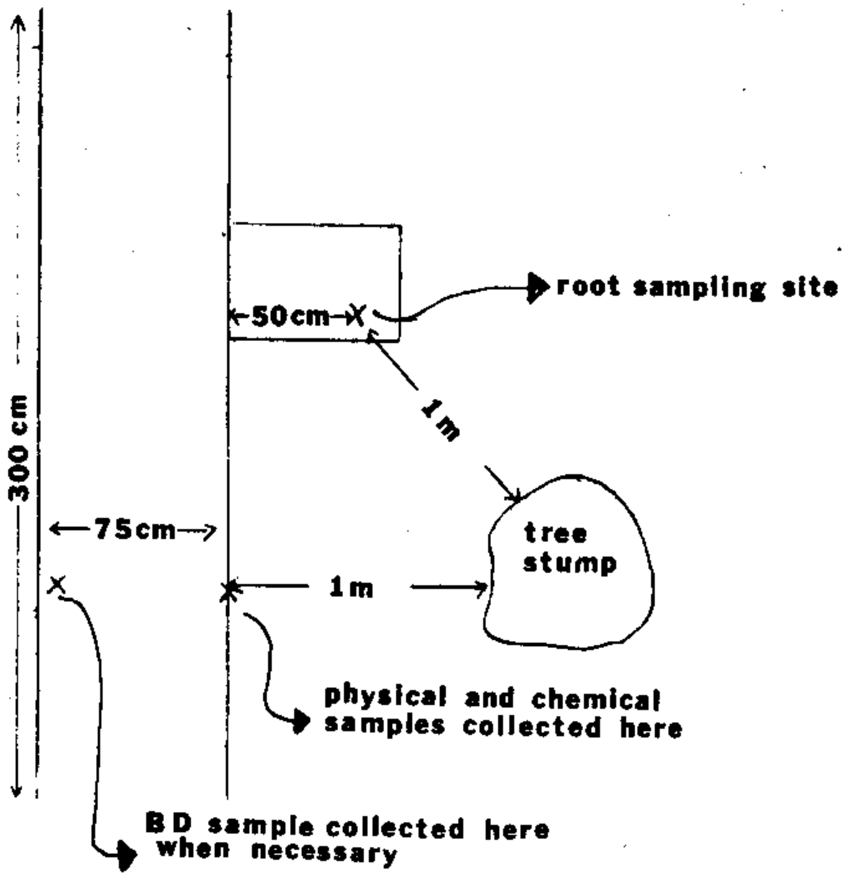


Figure 17. Components and operation of root sampler: A, sampler assembly; B, driving coring cylinder into ground; C, pulling cylinder from soil; D, extracting soil sample (from Jurgensen 1977).

Figure 18. Root and soil sampling procedure.



The machine (Fig. 19) was patterned after the one described by Rowse and Phi Hips (1974). Each 10 cm of soil core was wrapped in fine nylon mesh and soaked in water for approximately 12 hours. The soil was gently washed from the roots with a small stream of water. Roots were air-dried, placed between clear glass plates, and the plates placed on the machine. After the first reading was taken, the plates were turned at a 90° angle and a second reading was taken. The machine was calibrated so root length could be read directly in cm. The average of the two readings was recorded. Roots large enough to separate the plates by more than 0.5 cm were measured by hand.

Many fine mycorrhizal roots in the surface 10 cm soil sections were reduced to a fine powder upon drying and could not be measured. The values presented, therefore, for the surface soil underestimate the length and weight of the roots in the surface 10 cm of soil. In the case of root length this underestimation is probably substantial.

The values for the two sets of samples were averaged to give numbers used in the data analysis. Root data are presented by 10 cm intervals (Appendix D) and by 30 cm intervals (Table 6). An ANOVA and subsequent LSD ($\propto$ =0.05) were done for the 30 cm values by means of a SAS program. Significant differences within each profile by depth and between profiles at the same depth are indicated in Table 6.

In addition, the best two-model regressions were calculated using the physical and chemical soil values as independent variables with the dependent variables of root weight, percentage root weight (percentage root weight was calculated by dividing root weight for each 30 cm interval by total root weight), root length, and percentage root length (percentage root length was calculated by dividing root length for each 30 cm interval by total root length). Regression equations were developed for each 30 cm depth and then for alt depths combined. These values are reported in Table 7.

Figure 19. Diagram of the root length measuring machine: (a) General view of the instrument; (b) cross section through one of the runners; (c) a portion of the double lead screw; (1) motor; (2) intermediate platform; (3) photo-transistor housing; (4) toothed rack; (5) root platform; (6) glass plate; (7) pin; (8) microscope lamp; (9) base plate; (10) screw (from Rowse and Phillips 1974).

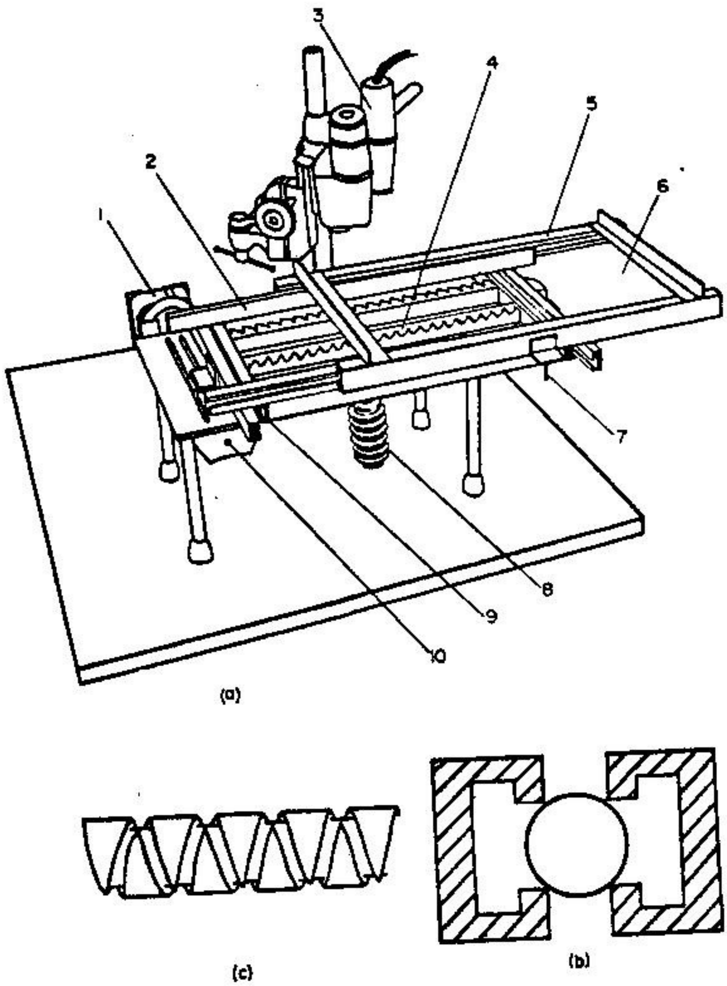


Table 6. Root length and weight data by 30 cm depths for the seven profiles.

Tree Species, Pit Number, and Root Length in cm per cm^3 of Soil

Depth	Variable	Black Oak	Black-jack Oak	Black Oak	Black-jack Oak	Black Oak	Black Oak	Post Oak
		One	Three	Four	Five	Six	Seven	Eight
A	RLCM	a 1.929a	a 2.289c	a 3.576c	a 2.823b	a 3.396b	a 3.540b	a 1.833b
B	RLCM	ab 0.918a	d 1.314b	cd 1.251a	bcd 1.077a	ab 0.948ab	a 0.678a	bc 0.978ab
C	RLCM	abc 0.762a	bc 0.825ab	abc 0.678a	a 0.336a	ab 0.528a	d 1.593a	c 0.969ab
D	RLCM	abc 0.708a	c 1.101ab		a 0.267a	ab 0.501a	bc 0.918a	ab 0.573a
E	RLCM	a 0.330a	a 0.276a		a 0.186a	ab 0.687a	a 0.308a	b 0.792ab

*Note: RLCM = root length in cm per cm^3 of soil.

Table 6. (continued).

		Tree Species and Pit Number						
Depth	Variable	Black Oak	Black-jack Oak	Black Oak	Black-jack Oak	Black Oak	Black Oak	Post Oak
		One	Three	Four	Five	Six	Seven	Eight
A	RLPC	a 41.859a	a 39.450c	a 64.869b	a 60.099b	a 57.999b	a 49.278b	a 36.360b
B	RLPC	bc 19.920a	c 22.629b	c 22.689a	c 22.911a	b 16.170ab	a 9.450a	bc 19.389ab
C	RLPC	bcd 15.741a	abc 14.220bc	abc 12.442a	a 7.179a	ab 9.021a	d 22.149ab	cd 19.191a
D	RLPC	bc 15.321a	c 18.951ab		a 5.850a	ab 8.541a	abc 12.771a	abc 11.340a
E	RLPC	a 7.160a	a 4.750a		a 3.960a	ab 8.269ab	a 6.350a	b 13.720ab

Note: RLPC = root length expressed as percent.

Table 6. (continued).

		Tree Species and Pit Number						
Depth	Variable	Black Oak	Black-jack Oak	Black Oak	Black-jack Oak	Black Oak	Black Oak	Post Oak
		One	Three	Four	Five	Six	Seven	Eight
A	RWMG	a 31.900a	a 11.100a	a 57.830a	a 8.538b	a 17.400b	a 26.343b	a 8.001ab
B	RWMG	b 47.320a	a 12.530a	a 3.888a	a 4.200a	a 5.892a	a 6.483a	a 4.149a
C	RWMG	ab 11.120a	a 1.445a	a 1.104a	a 0.651a	a 1.329a	a 6.006a	b 29.139b
D	RWMG	a 4.164a	a 1.445a		a 0.300a	a 0.426a	a 4.626a	a 2.031a
E	RWMG	a 1.054a	a 0.564a		a 0.238	a 1.668a	a 2.520a	a 1.116a

Note: RWMG = mg of root weight per cm^3 of soil.

Table 6. (continued).

Tree Species and Pit Number

Depth	Variable	Black Oak	Black-jack Oak	Black Oak	Black-jack Oak	Black Oak	Black Oak	Post Oak
		One	Three	Four	Five	Six	Seven	Eight
A	RWPC	a 33.390a	a 41.244a	a 92.040a	a 61.299b	a 66.429b	a 55.629b	a 18.000ab
B	RWPC	a 49.509a	a 46.581a	a 6.201a	a 30.150a	a 22.200a	a 13.689a	a 9.351a
C	RWPC	a 11.640a	a 5.400a	a 1.761a	a 4.680a	a 5.001a	a 12.681a	b 65.571b
D	RWPC	ab 4.359a	ab 5.400a		a 2.160a	a 1.611a	b 9.771a	ab 4.569a
E	RWPC	a 1.110a	a 1.390a		a 1.710a	ab 4.760a	b 8.230a	a 2.510a

*Note 1: Letters in the upper lefthand corner indicate significant differences between pits at the same depth. Letters in the lower righthand corner indicate significant differences between depths within the same pit. Means not sharing a letter a letter in common differ significant at the 0.05 level by the LSD Test.
*Note 2: RWPC symbolizes root weight in percent.

Table 7. Best two-model regressions by depths for selected variables.

Independent Variables

			1				2		
Depth	Dependent Variable	R^2	Name	B value	F value	Intercept	Name	B value	F value
A	Volume	0.59	NAC	-0.01	18.79	0.32	%N	-2.12	7.05
A	SI	0.56	K	-9.59	2.72	16.46	NAC	-0.31	20.24
A	RLCM	0.58	%0M	0.51	7.45	-1.34	%Si1t	0.02	7.75
A	RLPC	0.53	%0M	8.16	6.03	-20.35	%Si1t	0.39	6.66
A	RWMG	0.21	pH_w	28.95	4.31	-143.27	K	58.08	2.30
A	RWPC	0.31	%Si1t	0.57	4.41	-12.98	%Rock	-0.89	2.74
B	Volume	0.68	%Sand	0.01	8.21	0.26	RLCM	-0.60	23.67
B	SI	0.46	Ca	3.28	10.37	5.70	%Clay	0.06	5.56
B	RLCM	0.44	BS	-0.01	9.85	0.60	%N	-1.46	4.48
B	RLPC	0.64	BS	-0.24	27.89	12.95	%N	-26.32	5.03
B	RWMG	0.73	NAC	1.04	20.56	-26.44	%Sand	1.74	45.92
B	RWPC	0.41	NAC	1.22	5.38	-26.95	%Sand	2.01	11.79

Table 7. (continued).

Independent Variables

1							2		
Depth	Dependent Variable	R^2	Name	B value	F value	Intercept	Name	B value	F value
C	Volume	0.61	NA	-0.30	8.45	0.12	Mn	0.48	7.68
C	SI	0.60	pH_w	7.06	14.61	-25.47	Mn	19.20	15.45
C	RLCM	0.52	Na	-0.82	17.79	0.71	%N	-6.96	1.88
C	RLPC	0.56	Na	-15.12	22.87	5.74	Al	0.03	6.63
C	RWMG	0.25	pH_s	24.56	4.22	-92.79	%Sand	-0.47	3.20
C	RWPC	0.34	Ca	-8.74	7.67	-8.45	K	107.21	6.37
D	Volume	0.90	Mg	-0.08	106.54	0.57	Mn	-0.66	36.65
D	SI	0.63	Mg	-1.89	16.44	23.01	Mn	-21.14	10.50
D	RLCM	0.54	CEC	-0.03	16.64	1.07	%Rock	-0.01	6.70
D	RLPC	0.58	p	-0.56	6.69	7.67	Ca	-1.14	12.14
D	RWMG	0.50	pH_s	7.37	11.23	-27.57	P	-0.28	5.45
D	RWPC	0.57	pH_s	8.86	6.49	-29.69	CEC	-0.14	3.07

Table 7. (continued).

Independent Variables.

			1				2		
Depth	Dependent Variable	R^2	Name	B value	F value	Intercept	Name	B value	F value
E	Volume	0.90	pH_w	0.35	47.12	-1.56	Mn	0.80	12.14
E	SI	0.84	Mn	34.60	17.01	4.31	%Sand	0.36	10.99
E	RLCM	0.71	P_2O	0.04	7.18	-0.24	Al	0.05	14.60
E	RLPC	0.69	NAC	0.58	6.50	7.35	Mg	-597.52	12.36
E	RWMG	0.91	%OM	-1.00	5.98	9.12	Mg	-1.96	57.51
E	RWPC	0.95	Mg	-4.06	85.71	13.39	Mn	20.68	25.04
A11	Volume	0.22	BS	0.003	4.87	0.01	%Sand	0.01	17.70
A11	SI	0.14	pH_w	5.47	13.93	-15.44	Ca	1.04	9.30
A11	RLCM	0.59	Mn	0.07	42.73	0.12	%Silt	0.01	22.86
A11	RLPC	0.57	Mg	-2.22	21.72	-12.91	Mn	1.08	30.14
A11	RWMG	0.20	pH_s	21.76	12.26	-80.11	Mg	-1.05	3.81
A11	RWPC	0.25	Mg	-4.15	22.83	23.07	%Rock	-0.36	8.07

Note: SI = site index (height of the tree at fifty years).

Also, root weight, percentage root weight, root length, and percentage root length were plotted vs. every measured soil physical and chemical variable by 10 cm intervals for each profile.

Results and Discussion

Three tree species were sampled. In the list below tree species are given as well as the condition of the fragipan.

Profile 1. Black oak, no fragipan.
Profile 3. Blackjack oak, no fragipan changing to fragipan.
Profile 4. Black oak, fragipan present.
Profile 5. Blackjack oak, fragipan present.
Profile 6. Black oak, fragipan present.
Profile 7. Black oak, fragipan changing to no fragipan.
Profile 8. Post oak, no fragipan.

The use of three species as sample trees was somewhat undesirable because of the possibility of differences in inherent rooting patterns. However, it was necessary to choose these trees because they were dominants, and because they occupied the required landscape position. Differences in rooting patterns may be related to (1) species, (2) genetic differences within the same species, and (3) soil properties. In this discussion the assumption is made that only soil properties are responsible for differences in rooting patterns.

Graphical representation of root length and root weight of the seven profiles is presented in Figs 20,21,22a,22b,23,24,25, and 26. The relationships of root length and weight to soils will be discussed by 30 cm depths (depths A,B,C,D, and E).

Root length per unit volume of soil was greatest in the surface 30 cm of soil (depth A) for each profile except for profile 1. In profile 1 no significant difference in root length existed between depths; furthermore, root length was not significantly different between depths B,C,D, and E in any profile.

Although there were no significant differences in root length between profiles at depth A, there were significant differences at every other depth. At depth B, profile 3 had a significantly

Figure 20. Root Weight and Length Distribution in Profile 1.

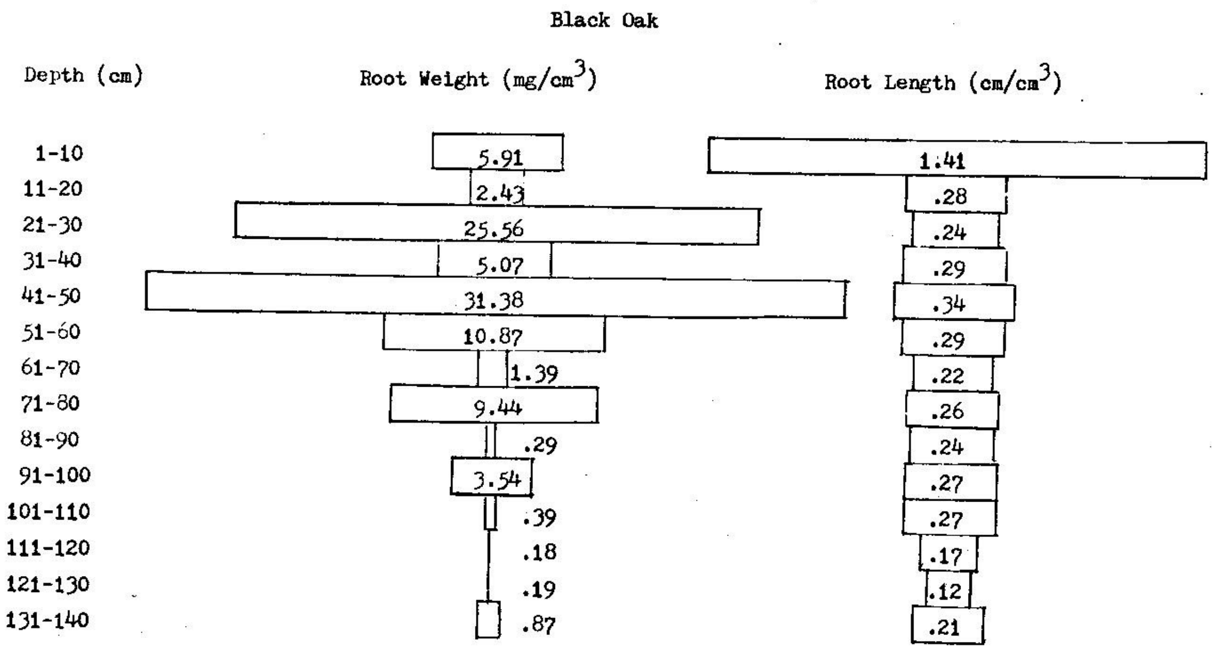


Figure 21. Root length and weight distributions in profile 3.

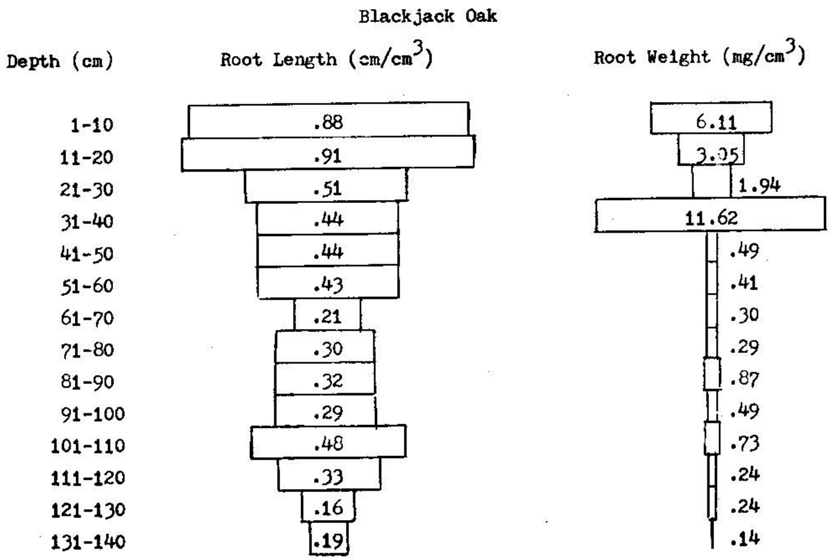


Figure 22a. Root length distribution in profile 4.

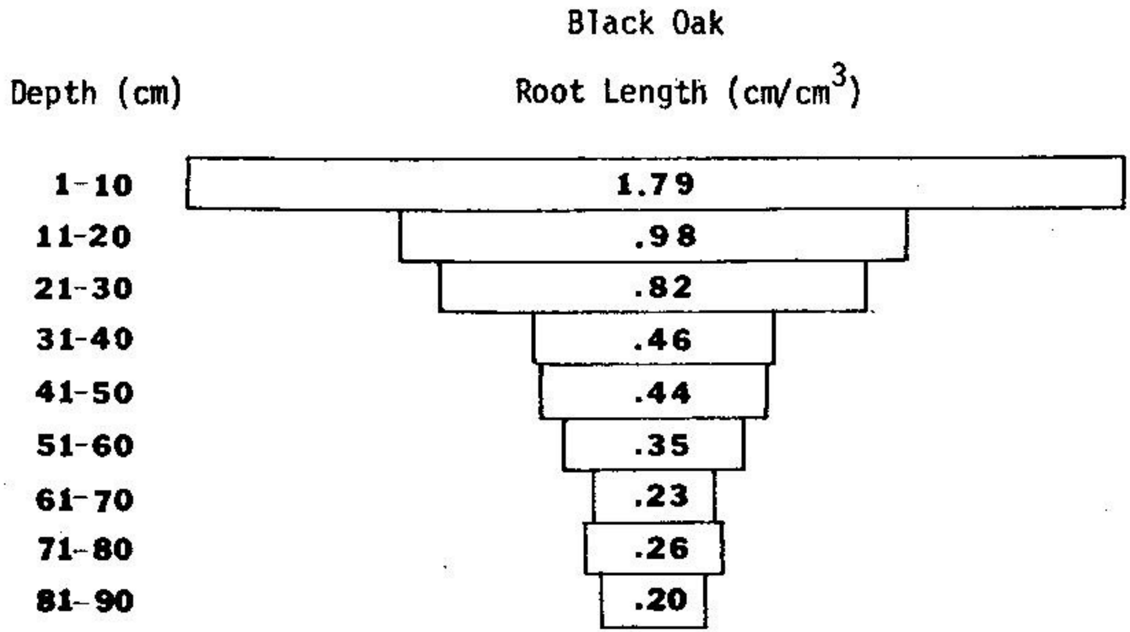


Figure 22b. Root weight distribution in profile 4.

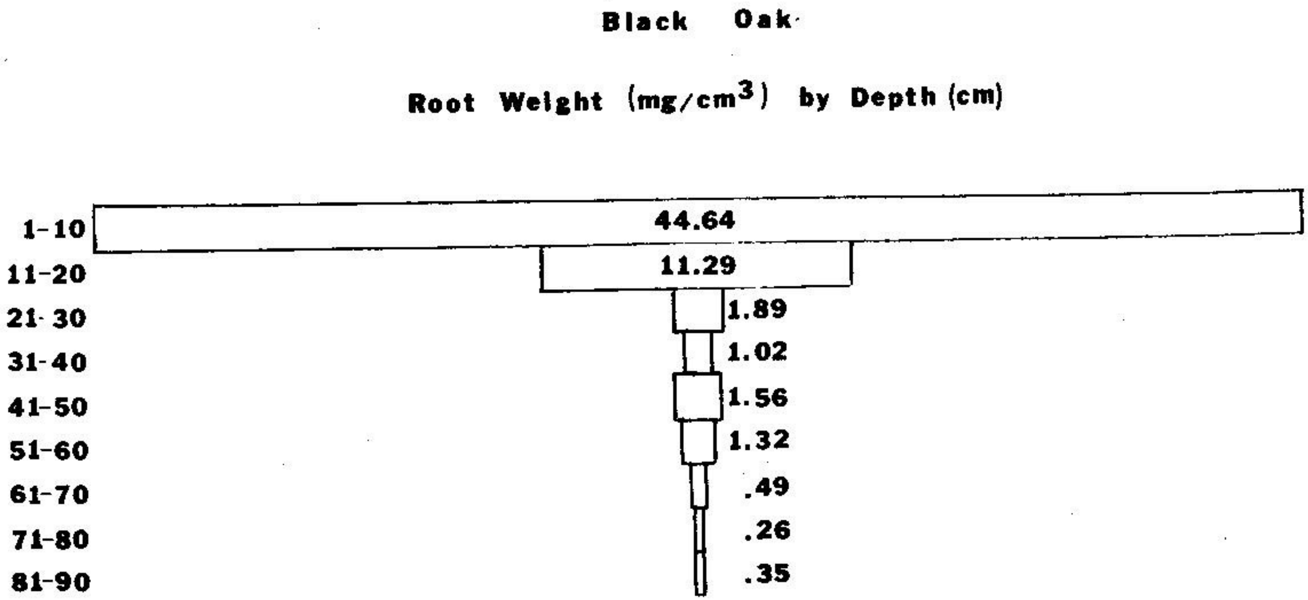


Figure 23. Root length and weight distributions in profile 5.

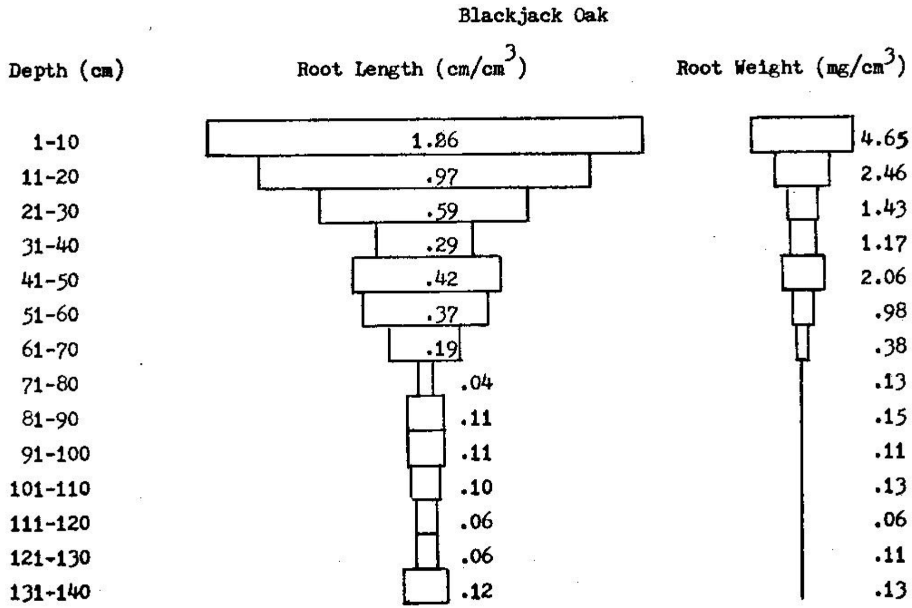


Figure 24. Root length and weight distributions in profile 6.

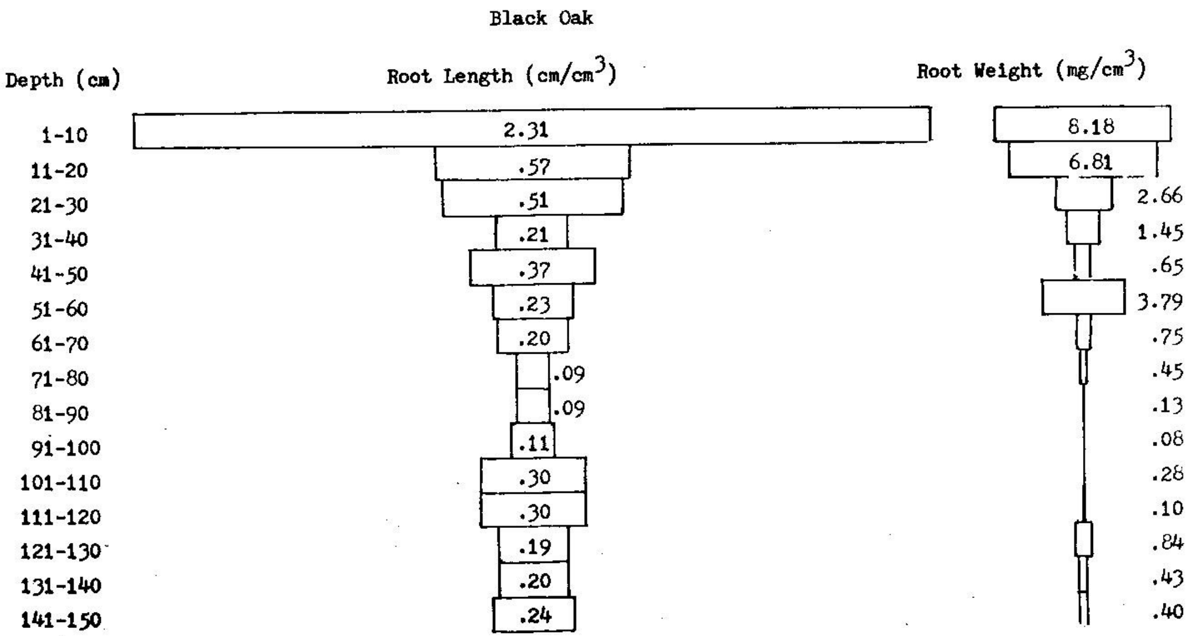


Figure 25. Root length and weight distributions in profile 7.

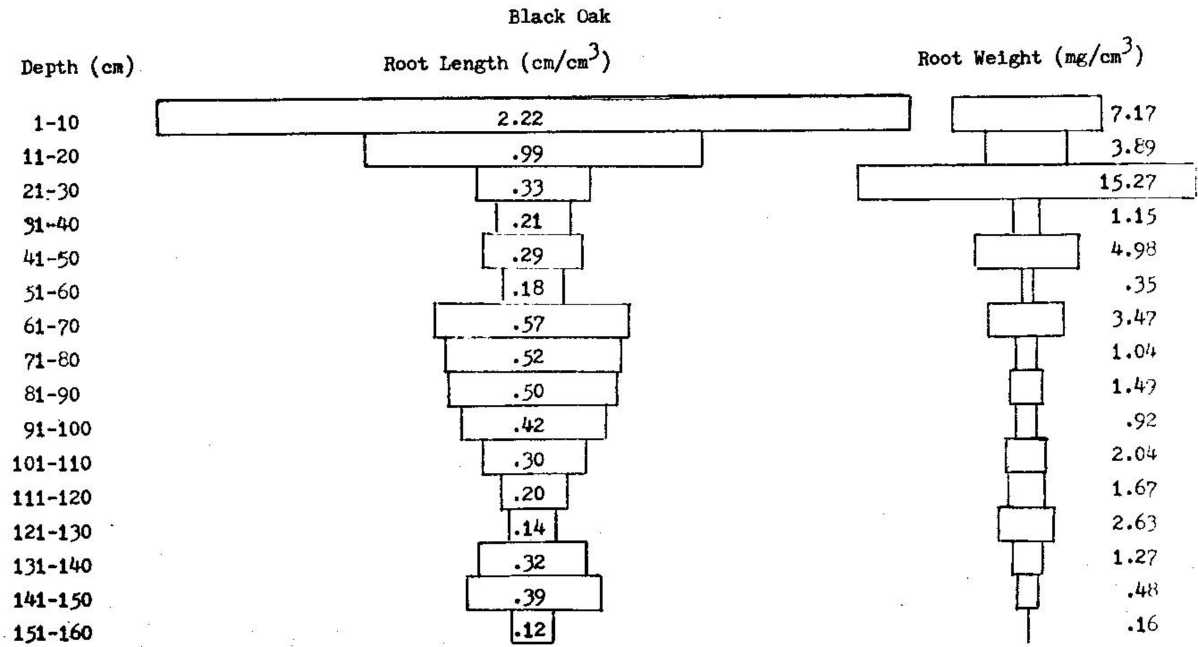
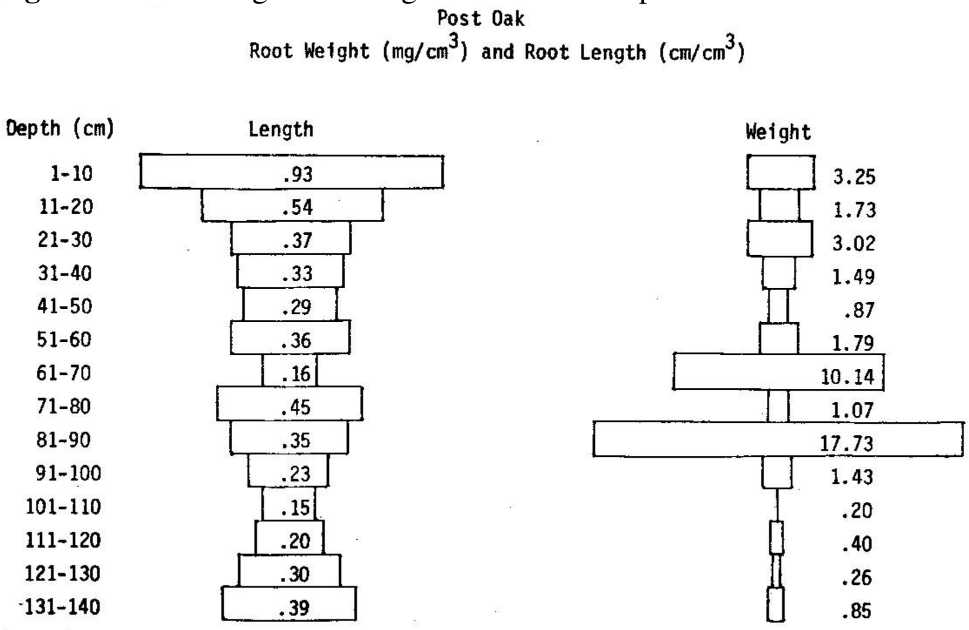


Figure 26. Root length and weight distribution in profile 8.



greater amount of root length than did profiles 6, 7, 8, and 1, but did not significantly differ from profiles 4 and 5. At depth C, profile 7 had a significantly greater concentration of roots than all other profiles. At depth D, there were fewer significant differences present. Profiles 1, 5, 6, and 8 did not show significant differences in root length. At depth E, there was still less variation with no significant difference between profiles 1, 3, 5, 6, and 7. Tests for significant differences using root length as percentage values indicated much the same pattern of significance as using root length (cm/cm^3).

There were fewer significant differences in root weight with depth than in root length. Profiles 1, 3, and 4 showed no significant difference between depths. Profiles 5, 6, and 7 had significantly more root weight in depth A than in underlying depths. There were no other significant differences present in profiles 5, 6, and 7.

Root weight at depth C in profile 8 was not significantly greater than root weight at depth A but was significantly greater than that of depths B, D, and E. A large lateral root sampled at this depth probably accounts for this pattern.

There were very few significant differences in root weight between profiles at the same depth. At depths A, D, and E no significant differences were observed. At depth B, profile 1 had a significantly greater root weight than any other profile. At depth C, profile 8 had a greater root weight than any other profile. Tests for significant differences using root weight values expressed as percentages indicated much the same pattern of significance as using root length (cm/cm^3) values.

Root weight (mg/cm^3) vs. Na (meq/100g) and root weight (mg/cm^3) vs. percentage rock by volume repeated a similar pattern for several profiles. As Na decreased in concentration (Fig. 27), root weight increased. The fact that both parameters decreased rather systematically with depth may explain this relationship. The same type of relationship was observed in root weight vs. percentage rock (Fig. 28).

The latter relationship is probably explained by the fact that as the amount of rock increased in the soil, available rooting space decreased.

The best two-model regressions for root weight, percentage root weight, root length, and percentage root length are presented in Table 7. Values for R^2 were about 0.5 except for depth E. At depth E, although there were fewer observations there was less variation in the values, and so a higher R^2 was obtained. The predictive power of these equations is questionable because of the large number of independent variables used and the relatively small number of root observations. These data suggest that the root distribution pattern between profiles is largely the same. The high bulk density values recorded for profiles 3, 4, 5, 6, and 7 apparently had little effect in limiting root growth. The fact that the fragipan was not strongly expressed in the area of root sampling probably explains this.

In the following discussion I offer several ideas that may explain the lack of fragic characteristics in the soil immediately adjacent to the tree roots examined in this study.

Historically, trees occupied this site well before the end of the Pleistocene (approximately 2,000,000–10,000 BP). Pollen studies done by King (1973) in the western Missouri Ozarks indicate a sequence of vegetative succession in the Wisconsin (60,000–approximately 10,000 BP) dating before 40,000 BP. His work suggests the following vegetative sequence:

- before 40,000 to 25,000–20,000 BP — open pine parkland
- 25,000–20,000 BP to at least 13,500 BP—spruce forest
- 13,500 BP to the present — deciduous elements completely replaced the spruce.

These drastic vegetative changes are thought to be the

result of climatic changes that accompanied periods of glaciation in the Wisconsin Age.

Figure 27. Root weight and sodium concentration in the seven profiles.

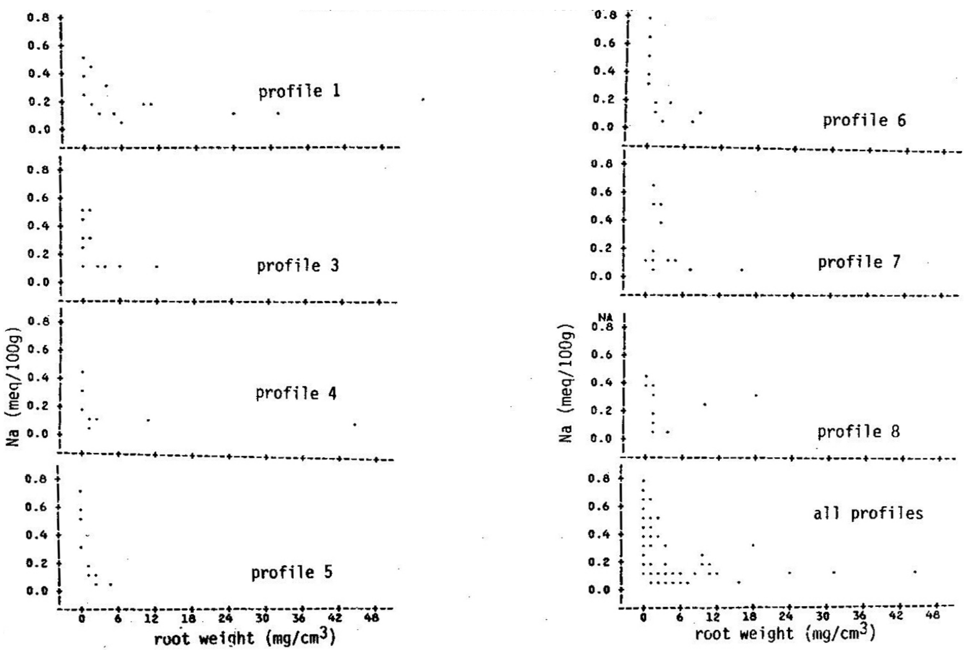
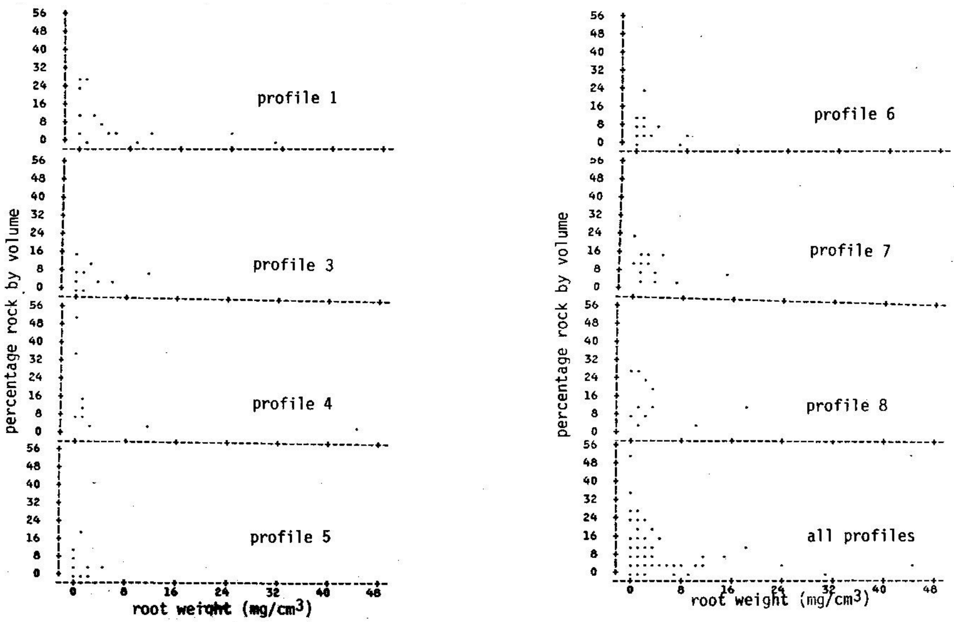


Figure 28. Root weight and percentage rock in the seven profiles.



Loess deposition on the site also occurred during the Wisconsin Age (Koenig 1961), with total accumulation on this site probably being about 1m. A precise date for fragipan formation cannot be given; however, the coniferous vegetation, which occupied the site for at least 26,000 years, must have contributed to the acidic nature of the soil. Because rates of loessial deposition were modest (occurring over a period of some thousands of years), and because total loess accumulation was relatively slight, plant growth was probably never seriously hampered. These conditions may also have played an important role in the formation of the fragipan itself.

Tree roots were present in the sol urn prior to fragipan formation and during fragipan formation. Once the fragipan was at least as well-expressed as it is today, it presented a considerable barrier to downward root movement. However, old root channels would have permitted access to underlying horizons by the roots. As new roots continued to develop and grow through the old root channels, the fragipan in the soil adjacent to the main body of roots may have been disrupted. During periods of excess soil moisture, clay particles could have moved downward, thus accounting for the high clay content in the lower depths of the profile.

Certain methods for evaluating site quality have been developed using fragic soil characteristics as a determining factor (Baker and Broadfoot 1978). Frequently, however, a forested area is harvested and then replanted with little attention to the presence or absence of fragipan horizons.

Due to the widespread occurrence of fragipan soils and their importance to forestry, some idea of their influence on tree height growth is needed. This part of the study was designed to determine the effect of a fragipan on oak growth on an upland forested site in south-central Missouri.

Literature Review

In a soil-geormorphic study in the Appalachian Plateau uplands of central New York, Hann et al. (1975) described the vegetation on a fragipan site:

> In the mid-1800's the area was logged of virgin timber and later partially cleared for farming. Present vegetation is primarily maple (*Acer saccharum* Marsh.), beech (*Fagus grandifolia* Ehrh.), and a few scattered hemlock (*Tsuga canadensis* (L) Carr.).

De Kimpe (1976) and De Kimpe et al. (1972) reported the following species on a fragipan soil in the Appalachian Highlands of Quebec, Canada: Fir (*Abies balsamea* (L.) Mill.), spruce (*Picea mariana* (Mill.) B.S.P.), sugar maple, beech, yellow birch (*Betula lutea* F. Michx), red maple (*Acer rubrum* L.), and alder (*Alnus rugosa* (Du Roi) Spreng.).

The effect of fragic horizons on water movement and the subsequent effect on species composition and tree growth also has been explored. There seems to be a

relationship between, drainage and fragipan expression with the fragipan best expressed in those areas where drainage is poorest (Grossman and Carlisle 1969). Fritton and Olson (1972) described water movement for a soil containing a fragipan in the northeast United States:

> Droughtiness comes about because the water storage capacity in the soil above the fragipan is low and because roots cannot penetrate the dense fragipan to remove additional water. Drainage problems occur because the fragipan is almost impermeable and water in the soil above the pan is frequently under pressure.

Working in the same part of the country, Patkovics and Petersen (1977) wrote:

> Fragipan soils in the northeast United States occur within the sloping, mountainous, watersheds drained by small streams. These soils have poor drainage and a shallow water table perched for long periods of time above the fragipan.

Ursic (1969) and Ursic and Duffy (1972), who investigated the establishment of pine plantations on eroded lands in Mississippi, also stressed the importance of fragipans to water movement:

> Storm runoffs were generally greater from watersheds with fragipan soils. Fragipans at shallow depths due to erosion increase runoff ... A relatively small proportion of fragipan or poorly drained soils on a drainage unit can apparently exert a relatively large influence on water yield. . . . High tree densities should be maintained of fragipan soils to maximize rainfall interception, depth of the forest floor, and

> potential soil-water storage.

On the Harvard Forest, Hatheway (1954) and Patric (1956) recognized the influence of a fragipan on soil water and the subsequent effect on the tree species composition of a given site. Lyford et al. (1963) who also worked on the Harvard Forest, reached several conclusions concerning the relationship of tree species composition to the presence of a fragipan: (1) White pine (*Pinus strobus* L.) was concentrated on many of the small areas where a fragipan was lacking. The lack of a fragipan presumably created a drier habitat to which pine was thought to adjust more successfully than hardwoods. (2) Distribution of white ash (*Fraxinus americana* L.) seemed closely related to variations in depth to the fragipan and the resultant soil moisture conditions. In areas where the fragipan was near the surface and the ground was frequently wet, higher concentrations of white ash were observed. (3) The growth of both pines and hardwoods was greater on till soils underlain by fragipans because of a more favorable soil moisture regime.

The last point is of interest because it contradicts the usual assumption that fragipans are detrimental to plant growth. In this case, improved growth was attributed to a greater supply of soil moisture above fragipan horizons. There have been other suggestions in the literature that fragipans may be of benefit or at least not detrimental to plant growth—given certain climatic-edaphic conditions. Wilde (1950, 1958) wrote:

> …the study of the suitability of Wisconsin soils for pulpwood production has revealed the highly beneficial effect of a lower stratum, undoubtedly due to a higher water retention. As a general rule, soils with compacted B-horizons, showing air permeabilities between 35 mm and 60 mm were found to support nearly double the volume of aspen and jack pine as compared

with soils underlain by pervious substrata showing a pressure of less than 10 mm.

Matthews (1974), in his discussion of indurated soils of the Penrith area of Cumbria, Great Britain, suggested such soils might not always be an agricultural limitation. He wrote:

> In areas with a relatively low annual rainfall and sandy soil, as in the Eden valley, induration can help to retain water in upper horizons and also act as a heat reservoir during the critical spring germination. Even though the fragic horizons with large bulk densities have a high thermal diffusivity, heat is trapped by layers of low bulk density and hence low thermal diffusivity, above and below. Heat is stored during the summer and slowly released during the winter and spring.

In a study designed to relate specific soil and topographic characteristics to site quality for black and white oaks in the Central Ozarks of Missouri, Watt and Newhouse (1973) reported almost identical site index averages and ranges for fragipan and non-fragipan soils. Their explanation for this was that

> . . . the small amount of additional water available in the non-pan soils (as compared to soils with a pan) is relatively unimportant. Although fragipans have structural cracks that are occasionally penetrated by roots, moisture below the pan is probably of little help to the tree because of the slow penetration rate of water through the pan during periods of moisture recharge."

In a related study, Graney and Ferguson (1972) examined

the relationship of soil and topography to the site index of shortleaf pine (*Pinus echinata* Mill.) on major soils of the Ozark Highlands. One of the factors they considered was depth to a fragic horizon. They concluded fragipans did affect the growth of shortleaf pine (Fig. 29) but added: "However, a possible contribution of fragipan layers to tree growth could be the reduction of water movement down through the profile during wet periods."

Francis (1978), who studied loblolly pine (*Pinus taeda* L.) growing on fragipan soils in Tennessee, concluded fragipan characteristics did not affect the site index or height growth of loblolly pine.

These last reports seem to be somewhat at odds with other reports about the effect of fragipans on tree growth in Missouri. For example, Fletcher and McDermott (1957), in a study of the influence of geologic parent material and climate on distribution of shortleaf pine in Missouri, suggested shortleaf pine was particularly susceptible to disease when subjected to periods of saturated soil conditions. They wrote:

> It appears these sites (with a fragipan) are seasonally either too wet or too dry (or both) for good growth and development of shortleaf pine. Indeed, the presence of post oak on the Lebanon silt loam suggests that it is better able to tolerate these moisture extremes than its associated species, including shortleaf pine.

Miller and Krusekopf (1918) echo this idea of reduced growth potential in their early publication on soils of Missouri:

> The Lebanon silt loam comprising the high flats with a well developed hardpan ... is so poorly drained naturally that its crop adaptations are rather limited. Today many of the areas are covered with a dense growth of post oak or

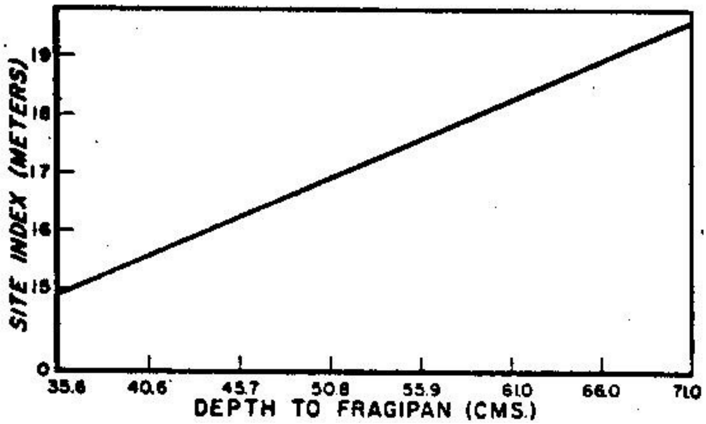
> black jack oak.

Writing nearly half a century later Krusekopf (1963) supported this idea further:

> A fragipan formation is considered the most significant single feature of the forest soils. The pan limits root penetration and therefore restricts the zone for obtaining a direct and consistent correlation between the abundance and height of post oak and the presence and degree of pan development of the pan horizon. When this is thick and near the surface, post oak is the dominant species and the trees are relatively short. Where the pan occurs at greater depths, other species tend to be more abundant.

Another important detriment is windthrow. Lyford and MacLean (1966) and Olson and Hole (1967-1968) have discussed this point in some detail. The latter investigators attributed the high frequency of wind-throw on forested soils of northern Wisconsin to the restriction of root growth by a fragipan and by cool temperatures present in the subsoil.

Figure 29. Changes in site index of shortleaf pine in the Ozark Highlands with changes in depth to fragipan soils (From Graney et al. 1972)



In conclusion, it seems there is no clear-cut influence of fragipans on tree growth in every situation. Depending on climatic conditions, depth to the fragipan, thickness of the fragipan, and the nature of overlying horizons the influence of the fragipan on tree growth fluctuates between being beneficial and detrimental.

Basic Question

Do trees growing on fragipans grow fairly well until a certain age and then decline markedly in growth?

Methods and Materials.

The trunk of each of the seven trees was cut 0.3 m above the ground and then sawn into 1 m sections. Trees selected were dominants. Species was not a selection criterion. The list that follows gives species by profile number and also

indicates presence or absence of the fragipan.

Profile 1. Black oak, no fragipan.
Profile 3. Blackjack oak, changing from non-fragipan to fragipan.
Profile 4. Black oak, fragipan.
Profile 5. Blackjack oak, fragipan.
Profile 6. Black oak, fragipan.
Profile 7. Black oak, changing from fragipan to non-fragipan.
Profile 8. Post oak, no fragipan.

After tree stems had been sectioned into 1 m lengths, a disk of wood was cut from the end of each section and labeled as to position in the stem and profile number for later analysis. The maximum and minimum diameters of each disk were measured to determine the average diameter. Along the line of this average diameter for each disk, five-year growth intervals were marked, starting from the cambium. These five-year growth intervals were then measured in cm and recorded.

Age, height, and volume curves were drawn based on height and diameter data. The age of each tree was assumed to be that found at stump height.

Best two-model regressions were developed with soil chemical and physical properties, root weight, and root length as the independent variables, and site index and volume at fifty years as the dependent variables. Regressions were calculated individually by depths (A, B, C, D, and E) and for all depths combined. Because of the small number of trees (seven) and the large number of independent variables used in the analysis, these regression equations are not conclusive.

It is also important to understand that in this part of the study comparisons of growth are not being made. The question is if a pronounced decrease in growth of those trees growing in soils with fragic characteristics as compared to those trees growing in soils without fragic

characteristics occurred.

Results and Discussion

Tree heights and volumes were low for all trees measured, but this is not surprising considering the low fertility status of the soil. The following list gives the height for each tree at fifty years (site index).

Profile 1. Black oak, 14.4 m (47.5 ft).
Profile 3. Blackjack oak, 9.1 m (30.0 ft).
Profile 4. Black oak, 11.4 m (37.6 ft).
Profile 5. Blackjack oak, 8.0 m (26.4 ft).
Profile G. Black oak, 14.4 m (47.5 ft).
Profile 7. Black oak, 12.7 m (41.9 ft).
Profile 8. Post oak, 12.4 m (40.9 ft).

The age and height curves for all seven trees are presented in Fig. 30. Volume growth through age fifty is given for each tree in Fig. 31. In Figs. 32 through 38 diameter and height growth by five year increments are graphically represented for each tree individually. The pattern throughout seems to be one of no abrupt decline in rate of growth at a given age.

The results of the regression analysis appear in Table 7. For all depths combined, R^2 values for volume and SI were .22 and .14, respectively. For individual depths, R^2 values ranged between .46 and .90. Although the latter value seems extraordinarily high, previously discussed limitations of the procedure indicate it would be ill-advised to overemphasize the validity of any of these regression equations.

Figure 30. Height growth of all trees.

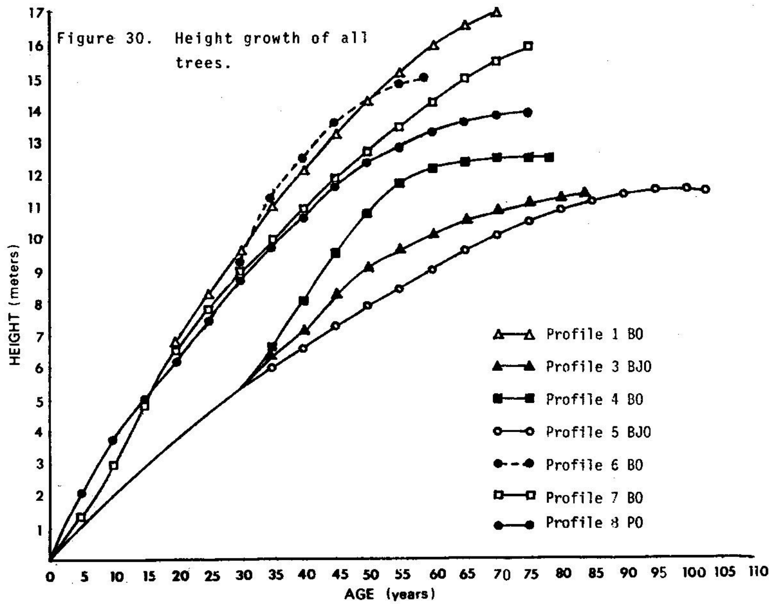


Figure 31. Volume growth of all trees.

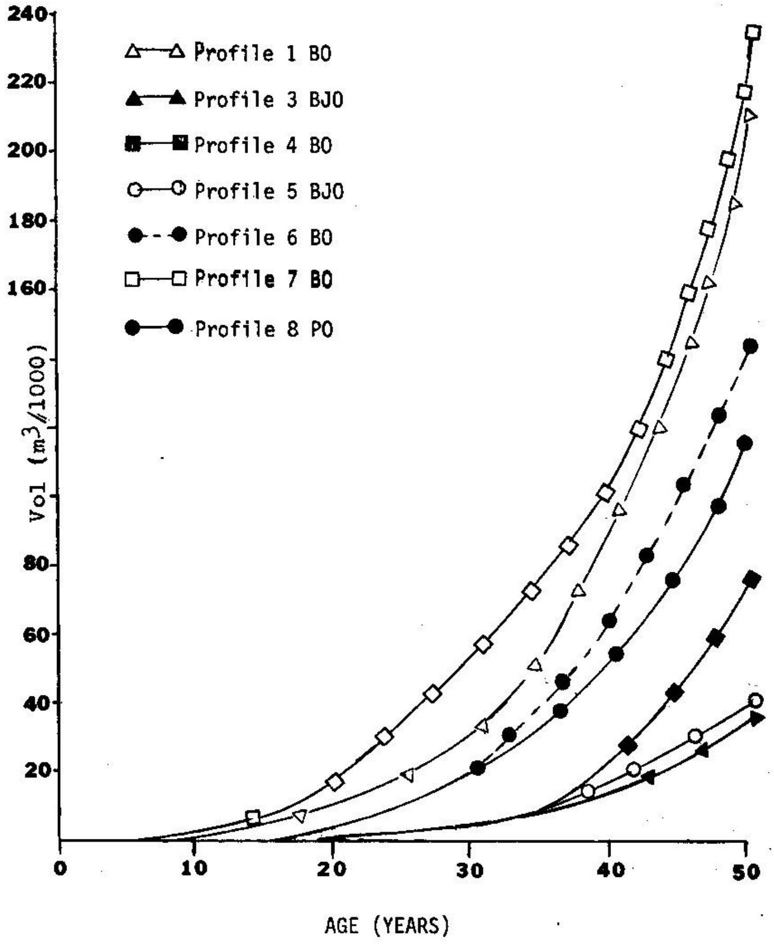


Figure 32. Height vs. age and height and diameter growth by five-year increments—profile 1, black oak.

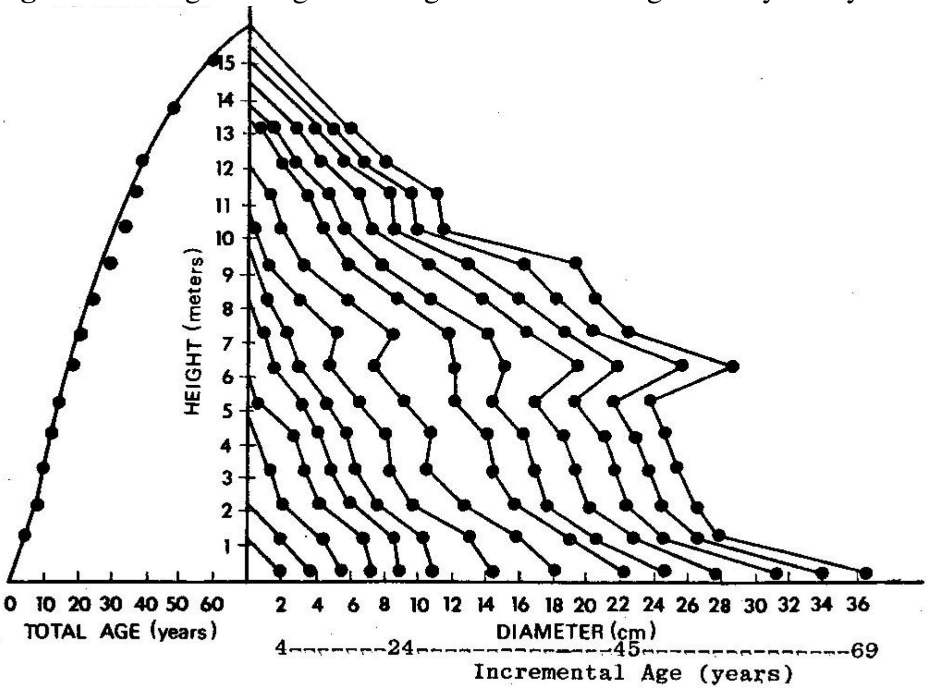


Figure 33. Height vs. age and height and diameter growth by five–year increments—profile 3, blackjack oak.

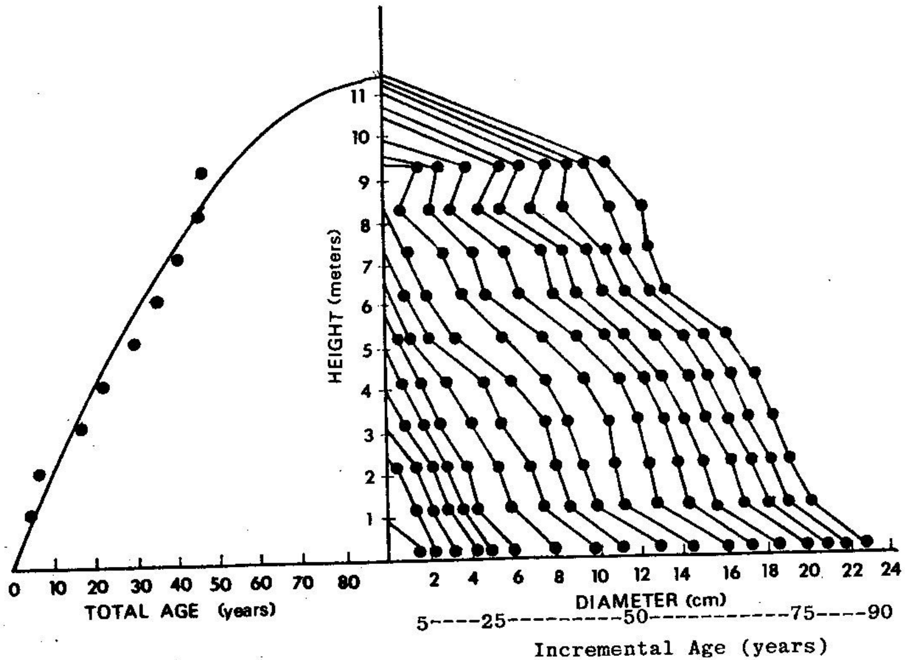


Figure 34. Height vs. age and height and diameter growth by five–year increments—profile 4, black oak.

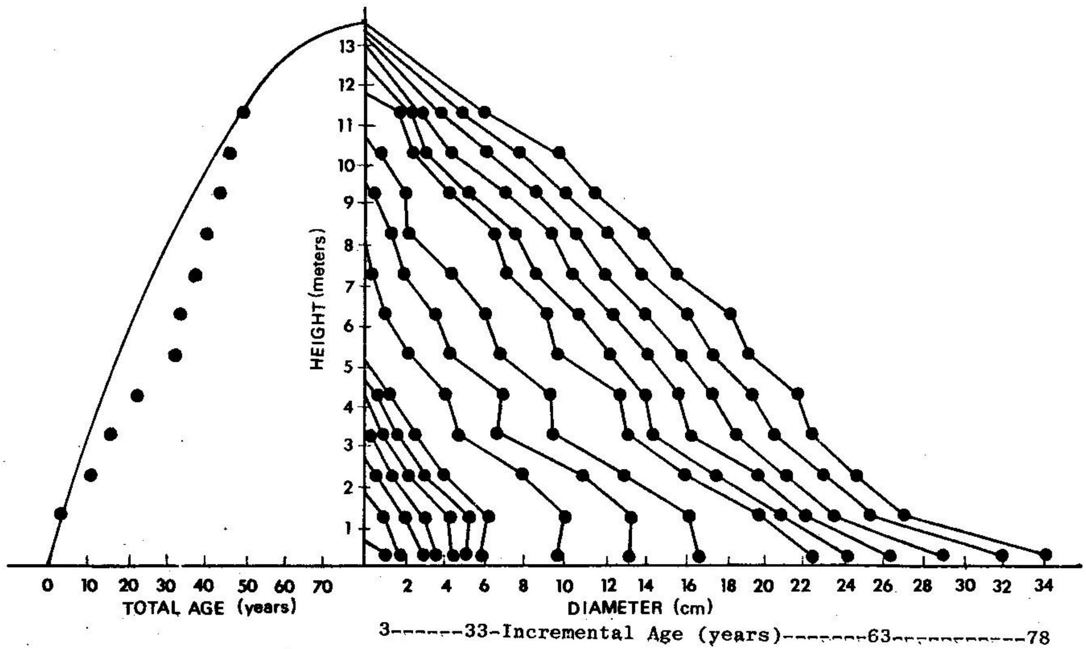


Figure 35. Height vs. age and diameter growth by five–year increments—profile 5, blackjack oak.

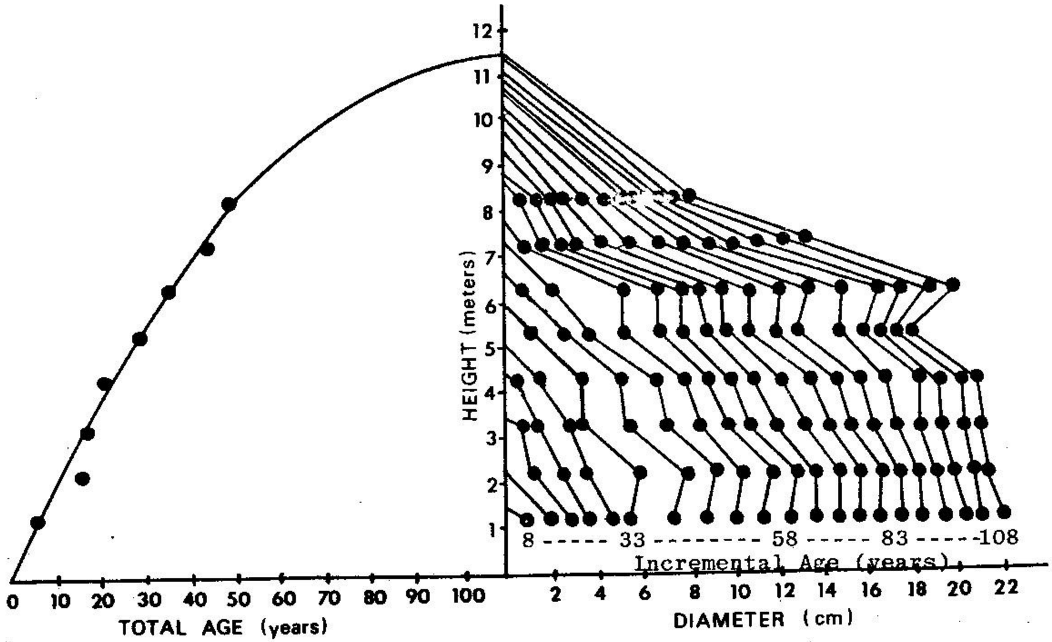


Figure 36. Height vs. age and height and diameter growth by five-year increments—profile 6, black oak.

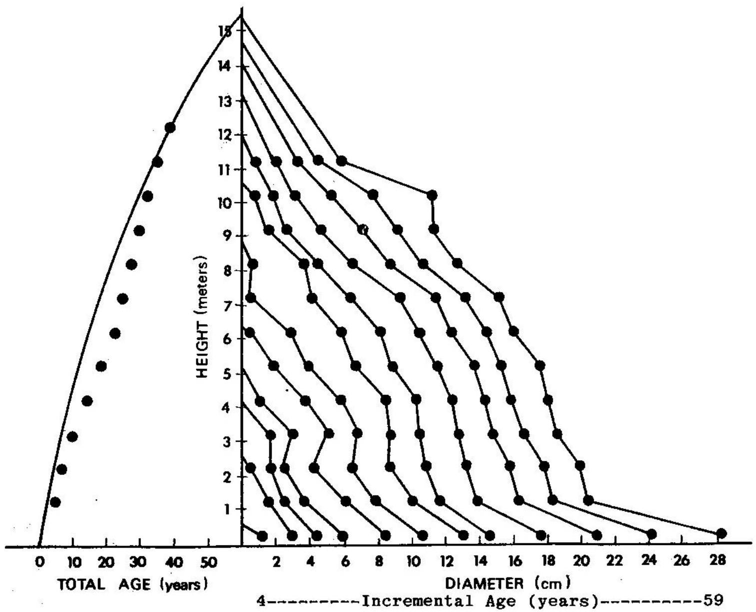


Figure 37. Height vs. age and height and diameter growth by five–year increments—profile 7, black oak.

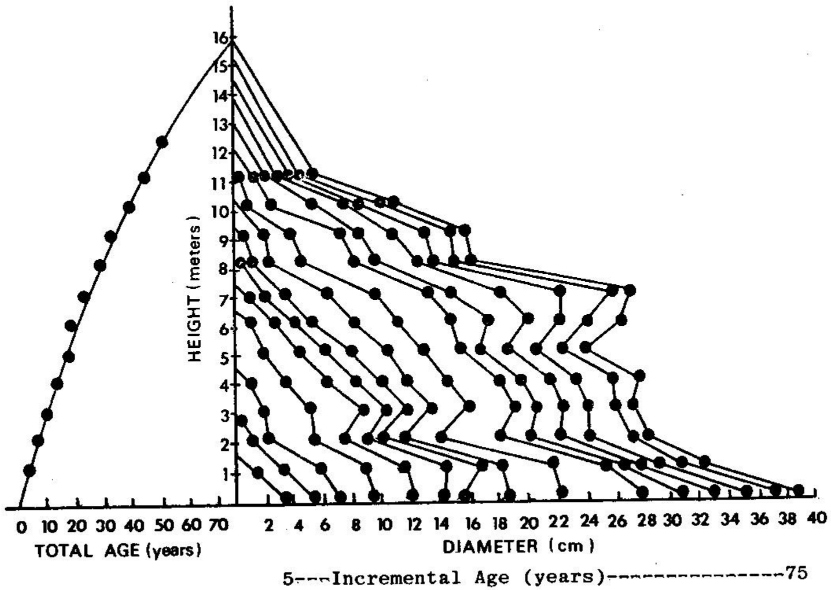
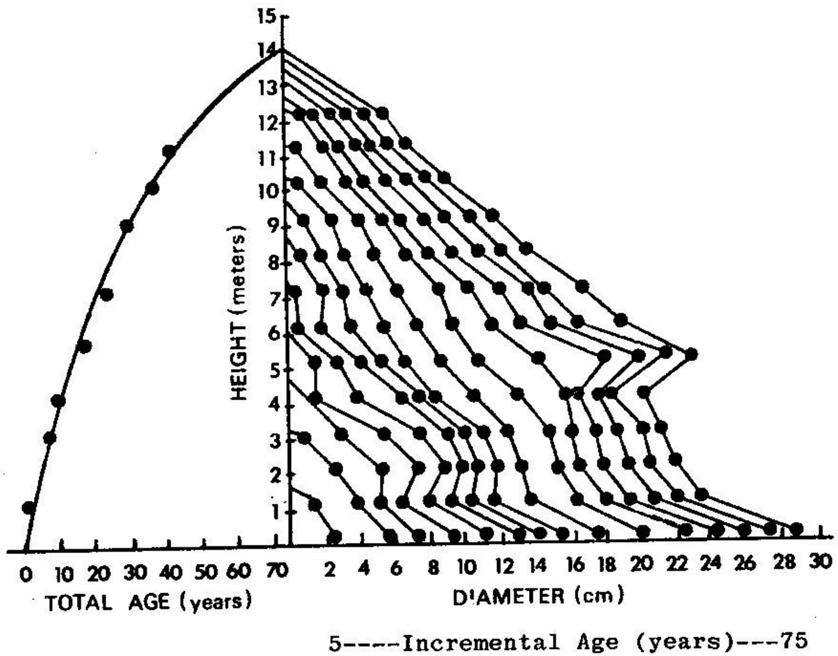


Figure 38. Height vs. age and height and diameter growth by five–year increments—profile 8, post oak.



Originally, it was thought members of the *Quercus* genus would probably show good growth on fragipan soils but after 20-40 years, growth rates would decline due to the inability of the tree's root system to effectively penetrate the fragipan. As tree size increased it was thought the soil available to the tree's root system would no longer be able to meet the nutritional and moisture needs required to sustain early growth rates. However, the data do not support this idea. No general decrease in rate of growth was observed for trees growing on fragipans soils as compared to non-fragipan soils.

As was pointed out in the chapter on rooting patterns, the fragipan is not thought to be a continuous unbroken body throughout the site but rather has many "holes" through which tree roots can penetrate underlying horizons. The downward movement of water would also be enhanced by these breaks in the fragipan. The general conclusion is, therefore, that trees growing on fragipans 30 cm or less in thickness will probably exhibit fairly constant growth similar to that of nearby trees growing on soils without fragic horizons.

It is not suggested that fragipans in general in the state of Missouri are non-limiting to plant growth. Bradford and Blanchar (1977) demonstrated the effectiveness of breaking up a strongly expressed fragipan on improvement of plant growth. It is suggested, however, that soils with fragipans of 30 cm or less in thickness are no greater risks for reforestation than are similar soils without fragipans, the reason being that the pan is not continuous but full of "holes" for which tree root systems past and present may be responsible. However, the low fertility status of these sites should be kept in mind. It is doubtful they are capable of producing high quality timber of any species in a short period of time without the addition of fertilizers.

SUMMARY

This study sought to examine tree growth and fragipan soils on an upland forested site in south-central Missouri. There were four parts to the study: (1) examining the relationship of the fragipan to landscape position; (2) examining physical and chemical properties on the study site and relating observed differences to the presence or absence of a fragipan; (3) examining the root distribution patterns of seven oak trees growing on the site; and (4) examining oak stem growth patterns on the site. Conclusions reached are presented below:

1) There was a relationship between elevation and fragipan development. The fragipan was expressed in the 996-975 ft to 1,000 ft elevation contours with the 1,000 ft elevation value being the highest point on the slope (summit position). The area in which the fragipan was developed occupied approximately three hectares (seven acres) of the nearly level to gently rolling ridgetop.
2) The measured chemical and physical properties indicated:
    a) A pan was absent in pits 1 and 8 which were the two ends of the transect line running over the ridgetop.
    b) A well-expressed pan was present in pits 3, 4, 5, 6, and 7 but was poorly expressed in the soil profiles 1 m from the base of each tree. The fragipan was not seen as continuously unbroken ever the area, but rather as a body full of "holes" largely the result of tree root action past and present.
    c) Few chemical and physical differences, with the exception of bulk density, were apparent between profiles that could be attributed to differences in fragic properties.
3) Few differences were apparent in patterns of root

distribution occurrence pits. This lack of difference is thought to be the result of the lack of strong fragipan expression in the profiles sampled.

4) Originally it was thought trees growing on fragic soils would show a period of declining rate of growth after 20-40 years of growth. The data indicated, however, that there was little difference in stem growth patterns of trees growing on fragic soils as compared to those growing on nearby soils without a fragic layer. Similarities in pH and aluminum values and penetration of tree roots through “holes” (areas of minimal fragic expression) in the fragipan were thought responsible for this.

REFERENCES

Arnold, R.W. 1975. Selected properties of New York soils with emphasis on rooting depth and available water-holding capacity. *Cornel University Agronomy Mimeo* 75-10.

Baker, J.B. and Broadfoot, W.M. 1978. A new technique of site selection for hardwoods. *Southern Journal of Applied Forestry* 2:42-43.

Batte, C.D. 1975. Rooting characteristics of slash pine (*Pinus elliottii* Engelm.) in relation to soil fragipans in the flatwoods section of southeast Texas. *Texas A&M University MS thesis*.

Batte, C.D. and Moehring, D.M. 1976. Rooting habits of slash pine in relation to fragipan characteristics. *Agronomy Abstracts* 1976:182.

Bradford, J.M. and Blanchar, R.W. 1977. Profile modification of a Fragiudatf to increase crop production. *Soil Science Society of America Journal* 41:127-131.

Carlisle, F.J., Knox, E.G., and Grossman, R.B. 1957. Fragipans in New York Soils: I. General characteristics and distribution. *Soil Science Society of America Proceedings* 21:320-321.

De Kimpe, C.R. 1976. Influence of parent material and moisture regime on soil genesis in the Appalachian Highlands, Quebec. *Canadian Journal of Soil Science* 56:271-283.

De Kimpe, C.R., Baril, R.W., and Rivard, R. 1972. Characterization of a toposequence with fragipan: the Leeds-Ste. Marie-Brompton series of soils, Province of Quebec. *Canadian Journal of Soil Science* 52:135-150.

Doll, John C. 1976. Hydraulic conductivities determined in situ for the Wilderness, Mexico and Menfro soils and used to predict soil water content. *University of Missouri-Columbia Ph.D. dissertation* pp 33 and 37.

Edmonds, Charles. 1976. Root growth, strength, and chemical properties of a Hobson fragipan. *University of Missouri-Columbia MS thesis*.

Fitzpatrik, E.A. 1956. An indurated soil horizon formed by permafrost. *Journal of Soil Science* 7:248-254.

Fletcher, P.M. and McDermott, R.E. 1957. Influence of geologic parent material and climate on distribution of shortleaf pine in Missouri. *University of Missouri-Columbia Research Bulletin* No. 625.

Francis, John. 1978. Fragipans do not reduce height growth of loblolly pine. *US Forest Service, Southern Forest Experiment Station* unpublished manuscript.

Franzmeir, D.P., Wiersma, D., Brownfield, S.H., Robbins, J.M., Jr., Shively, J.L., and Wingard, R.C. 1973. Water regimes of some Indiana soils. *Agriculture Experiment Station, Purdue University Research Bulletin* No. 904.

Fritton, D.D. and Olson, G.W. 1972. Bulk density of a fragipan soil in natural and disturbed profiles. *Soil Science Society of America Proceedings* 36:686-688.

Graney, D.L. and Ferguson, E.R. 1972. Shortleaf pine site-index relationships in the Ozark Highlands. *Soil Science Society of America Proceedings* 36:495-500.

Grossman, R.B. and Carlisle, F.J. 1969. Fragipan soils of the eastern United States. *Advances in Agronomy* 21:237-279.

Hallmark, C.T. and Smeck, N.E. 1979a. The effect of extractable aluminum, iron, and silicon on strength and bonding of fragipans of northeastern Ohio. *Soil Science Society of America Journal* 43:198-200.

Hallmark, C.T. and Smeck, N.E. 1979b. A rupture technique to determine fragipan strength. *Soil Science Society of America Journal* 43:198-200.

Hanna, H.E., Daugherty, L.A., and Arnold, R.W. 1975. Soil-geomorphic relationships in a first-order valley in central New York. *Soil Science Society of America Proceedings* 39:716-722.

Hatheway, William H. 1954. The influence of soil moisture on site in Tom Swamp I, Harvard Forest. *Harvard University MS thesis*.

Jurgensen, M.F., Larsen, M.J., and Harvey, A.E. 1977. A soil sampler for steep, rocky sites. USDA *Forest Service Research Note* INT-217.

Knox, E.G. 1957. Fragipan horizons in New York soils: III. The basis of rigidity. *Soil Science of America Proceedings* 21:326-330.

Krusekopf, H.H. 1963. Forest soil areas in the Ozark Region of Missouri, *University of Missouri Agriculture Experiment Station Research Bulletin* 818.

Lyford, W.H., Goodlett, J.C., and Coates, W.H. 1963. Landforms, soils with fragipans and forest on a slope in the Harvard Forest. *Harvard Forest Bulletin* No. 30.

Lyford, W.H. and MacLean, D.W. 1966. Mound and pit micro-relief in relation to soil disturbance and tree distribution in New Brunswick, Canada. *Harvard Forest Paper* No. 15.

Lyford, W.H. and Troedsson, T. 1973. Fragipan horizons in soils on moraines near Garpenberg, Sweden. *Studia Forestallia Suecica*, No. 8.

Matthews, B. 1976. Soils with discontinuous induration in the Penrith area of Cumbria. *Proceedings of the North of England Soils Discussion Group for 1974* 11:11-19.

Mclean, E.O. 1965. Aluminum. 1965. In Black, C.A. editor. *Methods of Soil Analysis, Part 2, Chemical and Microbiological*, American Society of Agronomy, Inc., Madison pp 978-998.

McNabb, David. 1972. Some soil-site relationships of a Typic Fragiudalf. *University of Missouri-Columbia MS thesis*.

McNabb, D.H. and Cox, G.S. 1973. Distribution of upland oak roots in a Typic Fragiudalf. *Agronomy Abstracts* 1973: 135.

McNabb, D.H. and Cox, G.S. 1976. Relationship between chemical and physical properties of an Aquic Fragiudalf and growth of Scarlet oak. In Fralish, J.S., Weaver, G.T., and Schlesinger, R.C. editors. *Proceedings of the First Central Hardwood Forest Conference*, Carbondale, Illinois pp 245-257.

Miller, F.P., Holowaychuk, N., and Wilding, L.P. 1971. Canfield silt loam, a Fragiudalf: I. Macromorphological, physical, and chemical properties. *Soil Science Society of America Proceedings* 35:319-324.

Miller, P.P., Wilding, L.P., and Holowaychuk, N. 1971. Canfield silt loam, a Fragiudalf. II. Micromorphology, physical, and chemical properties. *Soil Science Society of America Proceedings* 35:324-331.

Miller, M.F. and Krusekopf, H.H. 1918. The soils of Missouri. *University of Missouri Columbia, Agriculture Experiment Station Bulletin* No. 153.

Millet, J.L. and Collins, T.M. 1967. Fragipan soils and their effect off the rooting habit of trees. *Agronomy Abstracts* 1967 p 135.

Olson, G.W. and Hole, F.D. 1967-1968. The fragipan in soils of northwestern Wisconsin. *Transactions of the Wisconsin Academy of Sciences, Arts, and Letters* 56:173-184.

Palkovics, W.E. and Petersen, G.W. 1977. Contribution of lateral soil water movement above a fragipan to streamflow. *Soil Science Society of America Journal* 41:394-400.

Patric, James. 1956. The relationship of species distribution to soil moisture in Compartment I, Tom Swamp Block, Harvard Forest. *Harvard University MF thesis*.

Prasad, K.G. and Perkins, H.F. 1978. In situ hydraulic conductivity of a fragipan soil in the southern coastal plains. *Soil Science* 126:263-267.

Rowse, H.R. and Philips, D.A. 1974. An instrument for estimating the total length of root in a sample. *Journal of Applied Ecology* 11:309-314.

Scrivner, C.L. 1960. Morphology, mineralogy, and chemistry of the Lebanon Silt Loam, *University of Missouri-Columbia Ph.D. dissertation*.

Scrivner, C.L., Baker, J.C., and Miller, B.J. 1975. Soils of Missouri. *University of Missouri-Columbia Extension Publication* No. C823.

Smith, R.M. and Browning, D.R. 1946. Occurrence, nature, and land-use significance of "siltpan" subsoils in West Virginia. *Soil Science Society of America Proceedings* 62:307-317.

Soil Survey Staff. 1975. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. *USDA Handbook 436*. U.S. Government Printing Office, Washington, D.C.

Steele, F., Daniels, R.B., Gamble, E.E., and Nelson, L.A. 1969. Fragipan horizons and Be masses in the Middle Coastal Plain of north central North Carolina. *Soil Science Society of America Proceedings* 33:752-755.

Ursic, S.J. 1969. Hydrologic effects of prescribed burning on abandoned fields in northern Mississippi. *USDA Forest Service Research Paper* SO-46.

Ursic, S.J. and Duffy, P.D. 1972. Hydrologic performance of eroded lands stabilized with pine. *Proceedings, Mississippi Hater Resources Conference*, pp 203-216.

Watt, R.F. and Newhouse, M.E. 1973. Some soil phases in the Missouri Ozarks have similar site indexes for oaks. *USDA Forest Service Research Paper* NC-86.

Wilde, S.A. 1950. A simple soil air permeameter. *Agronomy Journal* 42:522.

Wilde, S.A. 1958. *Forest Soils*. Ronald Press Company, New York pp 187-189.

Winters, Eric. 1942. Silica hard-pan development in the red and yellow podzolic soil region. *Soil Science Society of America Proceedings* 7:437-440.

Yassoglou. N.J. 1959. Morphology and genesis of some soils containing fragipans in northern Michigan. *Michigan State University Ph.D. dissertation*.

Zachary, A.L. and Ulrich, H.D. 1965. Fragipans—what are they? *Purdue University Agriculture Experiment Station Research Progress Report* 184.

APPENDICES

APPENDIX A

SOIL PROFILE DESCRIPTIONS

PROFILE 1

Colors are for moist soil.

Al	0 – 9 cm (0 – 3.5 in). Dark brown (10YR 4/3) silt loam; weak fine granular structure; very friable (moist); abrupt smooth boundary.
A2	9-19 cm (3.5 – 7.5 in). Yellowish brown (10YR 5/4) silt loam; weak fine granular structure; very friable (moist); 5% rock; abrupt smooth boundary.
Bl	19 – 28 cm (7.5 – 11 in). Yellowish red (5YR 5/6) silty clay loam; weak fine subangular blocky structure; friable (moist); clear wavy boundary.
B21	28 – 61 cm (11 – 24 in). Yellowish red (5YR 4/6) silty clay; moderate medium subangular blocky structure; friable (moist); gradual boundary.
B22	61 – 89 cm (24 – 35 in). Strong brown (7.5YR 5/6) silty clay matrix with red (2.5YR 4/6) mottles; moderate fine subangular structure; firm (moist); gradual wavy boundary.
B3	89 – 123 cm (35 – 48.5 in). Strong brown (7.5YR 5/6) with dark yellowish brown (10YR 4/4), gray (10YR 5/1), and red (2.5YR 4/6) mottles; silty clay; moderate fine subangular blocky structure; firm (moist); 60% rock; gradual wavy boundary.
II B	123 cm + (48.5 in +). Gray (10YR 5/1), dark yellowish brown (10YR 4/4), strong brown (7.5YR 5/6), and gray (10YR 5/1); silty clay; strong medium subangular blocky structure; firm (moist); 75% sandstone rock.

PROFILE 3

Colors are for moist soil.

Al 0 – 8 cm (0 – 3 in). Brown to dark brown (10YR 4/3) silt loam; weak fine granular structure; very friable (moist); abrupt smooth boundary.

A2 8 – 13 cm (3 – 5 in). Yellowish brown (10YR 5/4) silt loam; weak medium granular structure; very friable (moist); abrupt smooth boundary.

Bl 13 – 20 cm (5 – 8 in). Brown to dark brown (7.5YR 4/4) light silty clay loam; weak medium subangular blocky structure; friable (moist); 10% rock; clear smooth boundary.

B21 20 – 43 cm (8 – 17 in). Brown to dark brown (7.5YR 4/4) heavy silty clay loam; weak medium subangular blocky structure; friable (moist); 5% rock; clear smooth boundary.

B22 43 – 66 cm (17 – 26 in). Dark yellowish brown (10YR 4/4) and brown to dark brown (7.5YR 4/4) heavy silt loam; moderate medium subangular blocky structure; friable (moist); clear wavy boundary.

B23 66 – 99 cm (26 – 39 in). Dark yellowish brown (10YR 4/4) matrix with reddish brown (5YR 4/3) and dark reddish brown (2.5YR 3/4) mottles; silty clay loam; moderate medium sub-angular blocky structure; friable (moist); clear wavy boundary.

IIA 99 – 122 cm (39 – 48 in). Gray (10YR 5/1) matrix with brown to dark brown (7.5YR 4/4) and dark red (2.5YR 3/6) mottles; silty clay; moderate coarse subangular blocky structure; friable (moist); 20% rock.

The description for this pit was made 1m from the base of a dominant blackjack oak tree. At this location a fragipan was not present. At 1m up the slope from the location for which the description was made the pan was expressed and was 10cm in thickness with the upper boundary 50 cm from the surface. At 2m and 3m up the slope from the area described the fragipan was 15cm thick with the upper boundary 44cm from the surface. At 4m up the slope the pan was 20cm thick and had an upper boundary 50cm from the surface.

Photographs of pit 3. Photograph A is from the lower end of the pit and photograph B is from the upper end of the pit. The distance between the two pit ends is approximately 4 m.

A

B

PROFILE 4

Colors are for moist soil.

Al 0 – 8 cm (0 – 3 in). Dark brown (10YR 4/3) silt loam; weak fine granular structure; very friable; many roots; clear smooth boundary.

A2 8 – 18 cm (3 – 7 in). Pale brown (10YR 6/3) silt loam; weak very fine granular structure; friable; many roots; abrupt smooth boundary.

B21 18 – 28 cm (7 – 11 in). Strong brown (7.5YR 5/6) silty clay loam; weak very fine subangular blocky structure; friable; common roots; clear smooth boundary.

B22t 28 – 58 cm (11-23 in). Light yellowish brown (10YR 6/4) silty clay loam; common fine prominent reddish brown (5YR 4/4) and few faint light brownish gray (10YR 6/2) mottles; weak very fine subangular blocky structure; friable; few fine roots; thin patchy clay films on face of peds; clear smooth boundary.

IIAx 58 – 76 cm (23 – 30 in). Light gray (10YR 7/2) silt loam; common fine distinct yellowish brown (10YR 5/6) and few fine brown (7.5YR 4/4) mottles; moderate very fine platy, breaking to very fine angular blocky structure; very firm and brittle; occasional vertical root channels filled with gray clay; 40% chert; clear smooth boundary.

IIB21x	76 – 97 cm (30 – 38 in). Brown (7.5YR 5/4) silty clay loam; common fine distinct yellowish red and few fine distinct gray (10YR 5/1) mottles; moderate fine angular blocky structure; firm; clay films on vertical and horizontal cleavages; few fine roots; clear smooth boundary.
IIB22x	97 – 109 cm (38 – 43 in). Dark gray (10YR 4/1) heavy silt clay loam; common fine faint dark yellowish brown (10YR 4/4) and few, fine prominent dark red (2.5YR 3/6) mottles; weak very fine angular blocky structure; 10% chert; gradual smooth boundary.
IIB23x	109 – 152 cm (43 – 60 in). Yellowish brown (10YR 5/4) silty clay loam; common fine prominent dark red (2.5YR 3/6) and few fine faint grayish brown (10YR 5/2) mottles; massive; firm; clay films; stone-size chert.

PROFILE 5

Colors are for moist soil.

Al	0 – 5 cm (0 – 2 in). Brown to dark brown (10YR 4/3) silt loam; moderate very fine granular structure.
A2	5 – 15 cm (2 – 6 in). Yellowish brown (10YR 5/4) silt loam; weak very fine granular structure.
Bl	15 – 23 cm (6 – 9 in). Strong brown (7.5YR 5/6) heavy silt loam; weak very fine subangular blocky structure.
B21	23 – 33 cm (9 – 13 in). Yellowish brown (10YR 5/4) silty clay loam; moderate very fine subangular blocky structure.
B22	33 – 53 cm (13 – 21 in). Brown (10YR 5/3) and dark brown (10YR 3/3) matrix; silty clay; moderate very fine subangular blocky structure.
B3x	53 – 69 cm (21 – 27 in). Gray (10YR 5/1), yellowish brown (10YR 5/4), and dark yellowish brown; silty clay loam; weak very fine subangular blocky structure; 35% rock.
IIB	69 – 152 cm (27 – 60 in). Gray brown (10YR 5/2), red (2.5YR 4/6) and yellowish brown (10YR 5/4); silty clay or clay; moderate medium and fine subangular blocky structure.

PROFILE 6

Colors are for moist soil.

A1	0 – 8 cm (0 – 3 in). Dark brown (10YR 3/3) silt loam; weak very fine granular structure; very friable (moist).
A2	8 – 18 cm (3 – 7 in). Yellowish brown (10YR 5/4 silt loam; weak very fine subangular blocky structure; very friable (moist).
Bl	18 – 43 cm (7 – 17 in). Brown to dark brown (7.5YR 4/4) silty clay loam; weak fine subangular blocky structure; friable (moist).
B21	43 – 66 cm (17 – 26 in). Yellowish brown (10YR 5/4) matrix with reddish brown (SYR 4/4) mottles; silty clay loam; weak fine subangular blocky structure; friable (moist); 25% rock.
B22	66 – 86 cm (26 – 34 in). Dark yellowish brown (10YR 4/4) matrix with pale brown (10YR 6/3) and gray (10YR 5/1) mottles; silty clay loam; weak medium platy structure; friable (moist); 10% rock.
IIB	86 – 142 cm (34 – 56 in). Yellowish brown (10YR 5/4), gray (10YR 5/1), and red (2.5YR 4/6); silty clay; strong medium subangular blocky structure; friable (moist); 25% rock.

PROFILE 6

Colors are for moist soil.

A1	0 – 5 cm (0 – 2 in). Dark brown (10YR 3/3) silt loam; weak fine granular structure; very friable; many roots; clear smooth boundary.
A2	5 – 13 cm (2 – 5 in). Light yellowish brown (10YR 6/4) silt loam; weak very fine granular structure; friable; many roots; abrupt boundary.
B21	13 – 28 cm (5 – 11 in). Strong brown (7.5YR 5/4) silty clay loam; weak very fine subangular blocky structure; friable; common roots; clear smooth boundary.
B22t	28 – 48 cm (11 – 19 in). Brown (7.5YR 5/4) light silty clay; moderate very fine subangular blocky structure; firm; common roots; thin platy clay films on ped surfaces; clear wavy boundary.
B23t	43 – 58 cm (19 – 23 in). Brown (10YR 5/3) light silty clay; weak fine subangular blocky structure; friable; few fine distinct red (10YR 4/8) mottles; thin continuous clay films; clear wavy boundary.
IIAx	58 – 76 cm (23 – 30 in). Grayish brown (10YR 5/2) silt loam; moderate fine platy breaking to weak very fine blocky structure; firm and brittle; 30% chert; gradual boundary.
IIBx	76 – 97 cm (30 – 38 in). Brown (10YR 4/3), dark yellowish brown (10YR 3/4) and dark red (10YR 3/6) silty clay loam; moderate very fine angular blocky structure; firm; gradual boundary.

IIB22 97 – 152 cm C38 – 60 in). Yellowish brown (10YR 5/4), gray (10YR 6/1) and dark red (10YR 3/6) silty clay loam; massive breaking to moderate coarse angular blocky structure; few fine roots; fine scattered chert fragments.

PROFILE 7

Colors are for moist soil.

Al	0 – 8 cm (0 – 3 in). Dark gray brown (10YR 4/2) silt loam; weak fine granular structure; very friable (moist); 30% rock.
A2	8 – 20 cm (3 – 8 in). Yellowish brown (10YR 5/6) silt loam; weak very fine subangular blocky structure; very friable (moist); 30% rock.
Bl	20 – 30 cm (8 – 12 in). Strong brown (7.5YR 5/6) silty clay loam; moderate very fine subangular blocky structure; friable (moist); 30% rock;
B21	30 – 48 cm (12 – 19 in). Strong brown (7.5YR 5/6) silty clay loam; weak subangular blocky structure; friable (moist); 20% rock.
B22	48 – 64 cm (19 – 25 in). Yellowish brown (10YR 5/4) silty clay loam; moderate fine subangular blocky structure; friable (moist); 20% rock.
IIAx	64 – 91 cm (25 – 36 in). Yellowish brown (10YR 5/4), light yellowish brown (10YR 6/4), and red (2.5YR 4/6) silty clay loam; moderate fine subangular blocky; friable (moist); 50% rock.
IIB	91 – 147 cm (36 – 58 in). Gray (10YR 5/1), dark red (2.5YR 3/6), and strong brown (7.5YR 5/6); silty clay; strong medium subangular blocky; friable (moist); 50% rock.

PROFILE 8

Colors are for moist soil.

Al	0 – 8 cm (0 – 3 in). Dark gray brown (10YR 4/2) silt loam; weak very fine granular structure; very friable (moist); 30% rock.
A2	8 – 32 cm (3 – 9 in). Yellowish brown (10YR 5/4) silt loam; moderate very fine subangular blocky; friable (moist); 30% rock.
Bl	32 – 43 cm (9 – 17 in). Strong brown (7.5YR 5/6) silty clay loam; moderate very fine subangular blocky structure; friable (moist); 30% rock.
B21	43 – 81 cm (17 – 32 in). Yellowish brown (10YR 5/4) matrix with red (2.5YR 4/6) mottles; silty clay; moderate medium subangular blocky structure; friable (moist).
B22	81 – 99 cm (32 – 39 in). Red (2.5YR 4/6), gray (10YR 5/1). And yellowish brown (10YR 5/4); silty clay; moderate fine subangular blocky; friable (moist); 40% rock.
IIB	99 – 140 cm (39 – 55 in). Strong brown (7.5YR 5/6), red (2.5YR 4/6), and gray (10YR 5/1); silty clay; moderate medium subangular blocky structure; friable (moist); 50% rock.
R	140 cm + (55 in +). Weathered sandstone with clay seams between rocks.

APPENDIX B

SOIL PHYSICAL PROPERTIES BY 10CM DEPTHS

Soil Physical Properties by 10cm Depths

Percent of < 2mm materials												
Pit No.	Depth cm	2-1 mm	1-.5 mm	.5-.25 mm	.25-.10 mm	.10-.05 mm	Total Sand	Silt .05-.002	Clay <.002	Class Name	Bulk Density g/cm^3	% > 2 mm by Vol.
1	5	3.35	2.93	5.79	3.98	3.96	20.01	65.00	14.99	SiL	1.48	5
1	15	1.97	2.15	4.70	3.46	3.27	15.55	56.65	27.80	SiCL	1.53	11
1	25	2.37	1.17	3.84	4.26	1.22	12.86	43.38	43.76	SiC	1.38	4
1	35	0.79	0.67	3.57	3.92	0.84	9.74	24.06	66.20	C	1.38	3
1	45	0.40	1.48	4.86	6.11	4.67	17.52	14.91	67.57	C	1.46	1
1	55	0.32	0.58	3.87	5.00	0.92	10.69	11.12	78.19	C	1.52	2
1	65	0.27	0.72	2.93	3.15	2.79	9.86	2.68	87.46	C	1.38	0
1	75	0.08	0.33	1.71	2.28	1.03	5.43	3.44	91.13	C	1.36	0
1	85	0.11	0.52	1.60	3.14	0.98	6.35	4.95	88.70	C	1.36	4
1	95	0.31	1.14	5.13	7.00	2.48	16.06	5.27	78.67	C	1.34	7
1	105	0.73	2.95	7.55	8.09	3.51	22.83	1.47	75.70	C	1.47	10
1	115	0.28	1.13	3.74	4.76	2.55	12.46	6.84	80.70	C	1.34	23
1	125	1.07	1.26	3.14	2.48	1.64	9.59	6.71	83.70	C	1.29	28
1	135	1.07	1.11	3.34	3.76	2.57	11.85	8.95	79.20	C	1.38	27

Soil Physical Properties by 10cm Depths

Percent of < 2mm materials												
Pit No.	Depth cm	2-1 mm	1-.5 mm	.5-.25 mm	.25-.10 mm	.10-.05 mm	Total Sand	Silt .05-.002	Clay <.002	Class Name	Bulk Density g/cm^3	% > 2 mm by Vol.
3	5	0.84	1.58	1.81	1.67	0.53	6.48	70.27	23.25	5	SiL	1.42
3	15	1.11	1.34	0.91	1.46	0.52	5.34	51.46	43.20	15	SiC	1.49
3	25	1.65	1.14	1.51	1.61	0.54	6.45	42.55	51.00	25	SiC	1.44
3	35	4.36	1.59	2.26	2.75	1.24	12.20	54.09	33.71	35	SiC	1.48
3	45	4.36	1.10	1.58	2.62	1.36	11.02	62.01	26.97	45	SiCL	1.38
3	55	1.62	0.61	1.35	1.90	1.00	6.48	55.14	38.38	55	SiC	1.49
3	65	0.75	0.57	3.60	3.25	1.06	9.23	11.72	79.05	65	C	1.40
3	75	0.36	0.95	4.03	5.43	1.75	12.49	9.99	77.52	75	C	1.39
3	85	0.37	0.95	2.98	4.30	1.98	10.58	9.12	80.30	85	C	1.30
3	95	0.49	0.91	2.27	3.02	1.99	8.68	10.52	80.80	95	C	1.33
3	105	0.23	0.55	1.53	1.79	1.87	5.97	10.60	83.43	105	C	1.41
3	115	0.49	1.06	1.37	1.37	1.20	5.49	11.51	83.00	115	C	1.30
3	125											
3	135											

Soil Physical Properties by 10cm Depths

Percent of < 2mm materials													
Pit No.	Depth cm	2-1 mm	1-.5 mm	.5-.25 mm	.25-.10 mm	.10-.05 mm	Total Sand	Silt .05-.002	Clay <.002	Class Name	Bulk Density g/cm^3	% >2 mm by Vol.
4	5	1.27	1.93	1.86	1.40	0.67	7.13	77,57	15.30	SiL	1.42	3
4	15	1.08	1.19	1.15	0.88	0.49	4.79	57.59	37.62	SiC	1.43	2
4	25	1.24	1.12	0.93	0.71	0.39	4.39	45.49	50.12	SiC	1.42	2
4	35	1.64	1.31	1.19	0.96	0.77	5.87	50.97	43.16	SiCL	1.45	10
4	45	2.53	1.35	1.59	1.88	0.72	8.07	52.82	39.11	SiC	1.43	17
4	55	1.07	0.68	0.71	1.28	1.05	4.79	56.91	38.30	SiC	1.66	7
4	65	0.78	0.65	0.73	1.09	1.15	4.40	44.59	51.01	SiC	1.87	8
4	75	0.78	0.70	0.69	0.89	1.07	4.13	25.82	70.05	C	1.59	35
4	85	0.62	0.72	1.00	0.79	1.37	4.50	11.35	84.15	C	1.55	52
4	95	0.48	0.55	1.24	1.94	1.12	5.33	13.52	81.15	C	1.69	
4	105	0.90	0.45	1.16	1.87	0.98	5.36	7.64	87.00	C	1.35	
4	115	0.48	0.49	1.11	1.42	1.23	4.73	5.27	90.00	C	1.37	
4	125	0.60	1.17	1.32	1.69	1.78	6.56	4.94	88.50	C	1.35	
4	135	0.49	0.97	1.32	1.87	1.37	6.02	3.48	90.50	C	1.38	

Soil Physical Properties by 10cm Depths

Percent of < 2mm materials												
Pit No.	Depth cm	2-1 mm	1-.5 mm	.5-.25 mm	.25-.10 mm	.10-.05 mm	Total Sand	Silt .05-.002	Clay <.002	Class Name	Bulk Density g/cm^3	% > 2 mm by Vol.
5	5	0.90	1.59	1.43	1.97	0.31	6.20	74.59	19.21	SiL	1.43	3
5	15	0.71	1.34	1.20	0.83	0.25	4.33	65.80	29.87	S1CL	1.40	1
5	25	0.54	1.12	1.09	0.95	0.30	4.00	53.70	42.30	SiC	1.44	1
5	35	0.51	1.15	0.67	1.18	0.39	3.90	47.30	48.80	SiC	1.64	1
5	45	0.92	1.51	1.66	1.57	0.74	6.40.	48.80	44.80	SiC	1.85	5
5	55	2.27	1.70	1.59	1.72	0.53	7.81	52.89	39.30	SiC	1.72	20
5	65	1.37	0.64	0.61	0.90	0.54	4.06	40.14	55.80	SiC	1.78	10
5	75	0.21	0.13	0.22	0.30	0.26	1.12	8.58	90.30	C	1.59	4
5	85	0.15	0.13	0.19	0.29	0.35	1.11	4.89	94,00	C	1.34	5
5	95	0.25	0.16	0.17	0.41	0.80	1.79	7.21	91.00	C	1.30	4
5	105	0.78	0.44	0.28	0.55	0.85	2.90	9.30	87.80	C	1.30	1
5	115	0.35	0.35	0.39	0.70	0.86	2.65	10.20	87.15	C	1.31	9
5	125	0.39	0.30	0.32	0.47	0.87	2.35	11.00	86.65	C	1.34	9
5	135										1.33	2

Soil Physical Properties by 10cm Depths

Percent of < 2mm materials												
Pit No.	Depth cm	2-1 mm	1-.5 mm	.5-.25 mm	.25-.10 mm	.10-.05 mm	Total Sand	Silt .05-.002	Clay <.002	Class Name	Bulk Density g/cm^3	% > 2 mm by Vol.
6	5	1.17	2.25	1.68	1.26	0.54	6.90	78.45	14.65	SiL	1.25	5
6	15	0.68	1.68	1.43	1.17	0.41	5.37	75.96	18.67	SiL	1.38	1
6	25	0.60	1.31	1.22	0.89	0.53	4.55	68.25	27.20	SICL	1.35	3
6	35	1.05	1.56	1.52	1.67	0.83	6.63	48.89	44.48	S1C	1.41	12
6	45	1.13	1.64	1.64	2.79	0.61	7.81	49.89	42.30	SiC	1.44	9
6	55	0.99	1.81	2.04	2.12	0.84	7.80	53.40	38.80	SiCL	1.51	9
6	65	5.94	2.19	2.01	2.07	1.51	13.78	60.42	25.80	SiCL	1.88	22
6	75	1.57	0.68	1.05	1.43	0.87	5.60	53.60	40.80	SiC	1.75	10
6	85	0.97	0.55	1.05	1.23	0.61	4.41	33.06	62.53	C	1.56	5
6	95	0.27	0.36	1.31	1.41	0.97	4.32	12.49	83.19	C	1.38	4
6	105	0.29	0.39	1.29	1.85	1.16	4.98	9.48	85.54	C	1.35	7
6	115	0.61	0.74	2.06	1.93	1.03	6.37	8.68	84.95	C	1.31	6
6	125	0.48	0.80	2.43	2.13	1.05	6.89	8.48	84.63	C	1.27	3
6	135	0.47	0.53	1.13	1.36	0.75	4.24	8.46	87.30	C	1.24	1
6	145											4

Soil Physical Properties by 10cm Depths

Percent of < 2mm materials												
Pit No.	Depth cm	2-1 mm	1-.5 mm	.5-.25 mm	.25-.10 mm	.10-.05 mm	Total Sand	Silt .05-.002	Clay <.002	Class Name	Bulk Density g/cm^3	% > 2 mm by Vol.
7	5	2.36	2.17	2.55	2.06	0.57	9.71	76.49	13.80	SiL	1.40	5
7	15	5.24	2.17	2.23	1.96	0.52	12.12	70.08	17.80	SiCL	1.39	9
7	25	7.43	2.47	2.41	1.96	0.44	14.71	59.49	25.80	SiC	1.41	7
7	35	8.70	2.81	1.97	1.40	0.36	15.24	51.46	33.30	SiC	1.46	10
7	45	2.86	1.84	2.46	2.37	0.62	10.15	59.55	30.30	SiCL	1.29	14
7	55	3.59	1.68	2.04	2.25	0.65	10.21	57.39	32.40	SiC	1.97	24
7	65	2.29	0.59	0.71	1.08	0.84	5.51	67.11	27.38	SiCL	1.81	4
7	75	1.70	0.57	0.58	0.80	0.67	4.32	57.28	38.40	SiC	1.55	6
7	85	3.64	1.39	1.23	1.36	0.59	8.21	40.89	50.90	SiC	1.65	5
7	95	5.11	1.25	1.40	1.53	0.64	9.93	41.67	48.40	SiC	1.54	8
7	105	4.80	1.27	0.77	0.84	0.49	8.17	31.88	59.95	C	1.85	14
7	115	2.07	0.68	0.53	0.52	0.42	4.22	19.88	75.90	C	1.44	9
7	125	1.32	1.19	0.82	0.78	0.67	4.78	17.62	77.60	C	1.39	11
7	135	1.91	1.20	0.76	0.70	0.65	5.22	7.86	86.92	C	1.32	9

Soil Physical Properties by 10 cm Depths

Percent of < 2mm materials												
Pit No.	Depth cm	2-1 mm	1-.5 mm	.5-.25 mm	.25-.10 mm	.10-.05 mm	Total Sand	Silt .05-.002	Clay <.002	Class Name	Bulk Density g/cm^3	% > 2 mm by Vol.
8	5	3.72	2.41	2.89	2.47	0.83	12.32	73.08	14.60	SiL	1.34	12
8	15	7.67	3.64	3.60	3.48	1.90	20.29	58.61	21.10	SIC	1.39	22
8	25	1.84	0.99	1.35	1.45	0.60	6.23	60.08	33.69	SiCL	1.44	18
8	35	2.12	1.25	1.73	1.87	0.84	7.81	59.09	33.14	SiC	1.43	13
8	45	1.69	0.85	0.97	1.08	0.67	5.47	52.22	42.31	SiC	1.38	5
8	55	0.28	0.25	0.37	0.41	0.28	1.59	18.31	80.10	C	1.34	7
8	65	0.32	0.20	0.24	0.27	0.22	1.25	10.69	88.06	C	1.27	5
8	75	0.47	0.32	0.28	0.58	0.63	2.38	9.07	88.55	C	1.24	4
8	85	0.65	0.37	0.35	0.57	0.75	2.69	9.26	88.05	C	1.28	10
8	95	0.41	0.44	0.60	1.62	2.60	5.67	14.28	80.05	C	1.31	11
8	105	0.43	0.38	0.41	1.30	1.47	3.99	11.46	84.55	C	1.31	9
8	115	0.17	0.36	0.50	1.38	2.00	4.41	18.04	77.55	C	1.23	7
8	125	0.09	0.28	0.44	1.13	2.25	4.19	22.26	73.55	C	1.24	29
8	135	0.10	0.25	0.60	1.57	5.16	7.62	24.83	67.55	C	1.25	26
8	145	0.29	0.36	0.88	3.50	5.42	10.45	18.05	71.50	C		

APPENDIX C

SOIL CHEMICAL PROPERTIES BY 10CM DEPTHS

Soil Chemical Properties by 10cm Depths

Pit No.	Depth in cm	pH_w	pH_s	% 0M	Na Meq/100g	P_2O_5 1bs/ac	Ca meq/100g	Mg meq/100g	K meq/100g	CEC meq/100g	BS %	NAC meq/100g	N % Total	Mn ppm	Al ppm
1	5	5.1	4.2	2.6	0.098	6	0.200	0.33	0.10	5.2	14	4.5	.043	6.3	27.0
1	15	4.0	4.1	1.1	0.109	6	0.325	1.00	0.11	9.5	16	8.0	.035	1.4	45.0
1	25	4.9	4.1	0.9	0.109	6	0.600	2.18	0.15	15.0	20	12.0	.039	0.5	69.5
1	35	5.0	4.1	0.8	0.141	6	0.800	3.00	0.15	20.6	20	16.5	.041	0.2	90.0
1	45	5.0	4.0	0.7	0.052	6	1.225	3.53	0.19	23.6	22	18.5	.041	0.3	97.0
1	55	5.0	4.1	0.7	0.207	3	0.450	3.96	0.22	25.8	23	20.0	.043	0.2	127.5
1	65	4.9	4.1	0.5	0.217	3	1.225	3.91	0.21	25.6	22	20.0	.036	0.2	105.0
1	75	4.8	4.1	0.4	0.217	3	1.325	4.09	0.24	25.9	23	20.0	.036	0.2	104.5
1	85	4.8	4.0	0.7	0.254	0	1.125	4.09	0.22	24.7	23	19.0	.033	0.2	118.5
1	95	4.8	4.0	0.7	0.315	0	1.075	3.71	0.20	22.8	23	17.5	.028	0.1	76.5
1	105	4.8	3.9	0.6	0.391	0	1.350	3.81	0.20	21.8	26	16.0	.021	0.1	78.0
1	115	4.6	3.9	0.7	0.391	3	1.550	4.00	0.20	25.1	24	19.0	.023	0.1	74.5
1	125	4.7	4.0	0.8	0.500	3	2.350	4.22	0.21	24.3	30	17.0	.023	0.2	50.0
1	135	4.7	4.1	1.1	0.478	6	2.125	3.79	0.21	20.6	32	14.0	.020	0.2	47.0

Soil Chemical Properties by 10cm Depths

Pit No.	Depth in cm	pH_w	pH_s	% 0M	Na Meq/100g	P_20_5 1bs/ac	Ca meq/100g	Mg meq/100g	K meq/100g	CEC meq/100g	BS %	NAC meq/100g	N % Total	Mn ppm	Al ppm
3	5	4.8	3.9	1.6	0.109	11	0.500	0.73	0.12	19.5	7	18.0	.048	3.8	45.5
3	15	4.9	4.1	1.5	0.141	3	2.125	3.63	0.23	20.6	30	14.5	.057	1.0	82.5
3	25	4.6	4.1	0.9	0.152	3	2.125	3.91	0.29	23.5	28	17.0	.056	0.9	108.5
3	35	4.9	4.1	1.1	0.141	3	1.125	2.48	0.18	16.9	23	13.0	.036	0.4	63.0
3	45	5.0	4.1	1.0	0.130	0	0.575	1.69	0.11	13.0	19	10.5	.027	0.2	44.0
3	55	4.9	4.1	1.0	0.141	0	0.800	2.92	0.16	21.0	19	17.0	.028	0.2	81.0
3	65	4.8	4.1	0.7	0.254	0	0.825	4.09	0.19	26.3	20	21.0	.029	0.2	119.5
3	75	4.8	4.1	0.5	0.315	0	0.800	4.22	0.17	24.5	22	19.0	.025	0.1	91.3
3	85	4.8	4.0	0.7	0.359	3	4.354	0.18	0.18	25.2	23	19.5	.024	0.1	84.0
3	95	4.9	4.0	0.6	0.435	3	0.775	4.12	0.17	25.0	22	19.5	.026	0.3	109.5
3	105	4.7	4.0	0.7	0.500	3	1.000	5.00	0.21	26,2	26	19.5	.026	0.2	93.0
3	115	4.7	4.0	0.6	0.56	3	1.225	5.75	0.25	27.8	28	20.0	.026	0.1	93.5

Soil Chemical Properties by 10cm Depths

Pit No.	Depth in cm	pH_w	pH_s	% 0M	Na Meq/100g	P_20_5 1bs/ac	Ca meq/100g	Mg meq/100g	K meq/100g	CEC meq/100g	BS %	NAC meq/100g	N % Total	Mn ppm	Al ppm
4	5	5.1	4.2	2.1	0.109	6	0.550	0.43	0.25	5.8	23	4.5	.054	5.4	18.5
4	15	4.9	4.1	1.8	0.130	8	0.275	1.24	0.21	11.9	24	9.0	.049	2.4	56.5
4	25	4.8	4.1	1.6	0.130	6	0.875	2.36	0.25	18.6	19	15.0	.050	1.2	75.0
4	35	4.8	4.0	1.5	0.152	11	0.625	2.94	0.26	17.0	23	13.0	.049	0.6	89.5
4	45	4.8	3.9	0.7	0.089	11	0.775	2.19	0.20	17.3	19	14.0	.041	0.2	71.0
4	55	4.8	3.8	0.8	0.130	13	0.775	1.91	0.19	18.0	17	15.0	.040	0.2	73.0
4	65	4.8	3.9	2.6	0.185	35	0.350	1.95	0.17	17.6	15	15.0	.027	0.2	66.0
4	75	4.8	4.0	1.9	0.315	3	0.400	2.57	0.19	22.5	15	19.0	.030	0.2	111.5
4	85	4.9	4.0	1.3	0.457	3	0.600	2.85	0.21	25.1	16	21.0	.032	0.2	124.0
4	95	4.9	3.9	0.5	0.435	6	1.025	3.03	0.18	25.2	19	20.5	.025	0.7	109.5
4	105	4.8	4.0	0.4	0.565	6	1.125	3.00	0.19	24.9	20	20.0	.025	0.2	99.0
4	115	4.8	3.9	0.3	0.587	6	1.400	3.17	0.21	26.4	20	21.0	.023	0.2	106.0
4	125	4.8	3.9	0.3	0.685	6	1.525	3.29	0.26	25.8	22	20.0	.028	0.1	92.5
4	135	4.6	3.0	0.4	0.750	11	1.925	3.69	0.32	27.2	25	20.5	.022	0.2	83.0

Soil Chemical Properties by 10cm Depths

Pit No.	Depth in cm	pH_w	pH_s	% 0M	Na Meq/100g	P_20_5 1bs/ac	Ca meq/100g	Mg meq/100g	K meq/100g	CEC meq/100g	BS %	NAC meq/100g	N % Total	Mn ppm	Al ppm
5	5	4.8	3.9	0.8	0.076	11	0.550	0.51	0.12	17.8	7	16.5	.042	4.3	49.5
5	15	4.8	3.9	1.0	0.098	20	0.550	0.98	0.13	11.7	15	10.0	.042	0.8	69.0
5	25	4.7	3.9	0.9	0.141	28	0.675	2.42	0.22	21.0	16	17.5	.056	1.1	116.5
5	35	4.7	3.9	0.6	0.163	13	0.775	3.48	0.26	23.7	20	19.0	.047	0.8	136.5
5	45	4.3	3.8	0.8	0.163	11	0.700	3.13	0.24	23.2	18	19.0	.052	0.6	119.0
5	55	4.7	3.8	0.9	0.207	11	0.775	2.61	0.20	20.8	18	17.0	.038	0.3	101.0
5	65	4.4	3.9	1.2	0.337	3	1.525	3.07	0.23	23.2	22	18.0	.023.	0.2	109.5
5	75	4.3	3.9	0.4	0.500	3	2.325	4.42	0.33	28.6	27	21.0	.026	0.2	109.5
5	85	4.3	3.9	0.6	0.587	3	2.575	4.53	0.34	29.0	28	21.0	.026	0.2	129.5
5	95	4.3	3.8	0.7	0.630	3	2.675	4.46	0.37	28.1	29	20.0	.025	0.2	109.0
5	105	4.3	3.9	0.8	0.565	3	3.200	4.38	0.39	28.5	29	20.0	.026	0.3	87.0
5	115	4.4	3.9	0.8	0.630	3	3.525	4.59	0.46	28.2	33	19.0	.066	0.2	70.5
5	125	4.4	3.9	1.0	0.707	0	3.200	3.81	0.41	27.1	29	19.0	.030	0.1	69.5

Soil Chemical Properties by 10cm Depths

Pit No.	Depth in cm	pH_w	pH_s	% 0M	Na Meq/100g	P_20_5 1bs/ac	Ca meq/100g	Mg meq/100g	K meq/100g	CEC meq/100g	BS %	NAC meq/100g	N % Total	Mn ppm	Al ppm
6	5	5.0	4.1	2.0	0.120	8	1.025	0.63	0.14	6.9	28	5.0	.067	10.7	24.0
6	15	4.9	4.1	0.9	0.098	11	0.800	0.79	0.13	7.3	25	5.5	.041	3.2	28.5
6	25	4.8	3.9	1.1	0.098	13	0.900	1.48	0.14	11.1	24	8.5	.043	1.3	49.0
6	35	4.6	3.9	0.8	0.152	13	1.350	3.00	0.26	21.8	22	17.0	.032	1.2	57.0
6	45	4.6	3.8	0.7	0.163	20	1.325	3.37	0.30	21.7	24	17.0	.043	0.8	103.5
6	55	4.7	3.9	1.5	0.185	23	1.525	2.78	0.29	22.8	21	18.0	.038	0.4	95.0
6	65	4.7	3.9	2.2	0.217	8	1.375	2.03	0.21	12.4	31	8.5	.026	0.3	57.5
6	75	4.8	3.9	2.0	0.326	6	1.725	2.33	0.20	20.6	22	16.0	.021	0.2	76.0
6	85	4.7	3.9	1.1	0.424	3	2.350	3.03	0.22	21.0	29	15.0	.024	0.2	108.5
6	95	4.7	4.0	0.9	0.500	6	2.800	3.53	0.25	30.6	23	23.5	.025	0.2	110.5
6	105	4.7	3.9	0.6	0.565	3	2.875	3.33	0.26	29.0	24	22.0	.022	0.2	94.5
6	115	4.4	3.9	1.4	0.696	0	3.375	3.72	0.31	27.1	30	19.0	.021	0.2	93.5
6	125	4.4	3.9	0.7	0.815	0	3.700	3.81	0.36	28.2	31	19.5	.022	0.2	101.0
6	135	4.3	3.8	0.8	0.772	3	4.050	4.03	0.39	28.7	32	19.5	.025	0.2	68.5

Soil Chemical Properties by 10cm Depths.

Pit No.	Depth in cm	pH_w	pH_s	% 0M	Na Meq/100g	P_2O_5 1bs/ac	Ca meq/100g	Mg meq/100g	K meq/100g	CEC meq/100g	BS %	NAC meq/100g	N % Total	Mn ppm	Al ppm
7	5	4.9	4.2	2.2	0.098	8	1.350	0.53	0.23	7.2	31	5.0	.022	13.1	22.0
7	15	4.5	4.0	1.7	0.109	6	1.100	0.48	0.21	6.4	30	4.5	.037	3.0	31.5
7	25	4.5	4.0	1.6	0.098	3	1.450	1.29	0.28	10.1	31	7.0	.044	1.7	50.0
7	35	4.5	4.0	1.5	0.076	3	1.475	2.13	0.30	12.0	33	8.0	.042	0.8	66.5
7	45	4.6	4.0	1.2	0.109	3	1.750	2.45	0.25	13.6	34	9.0	.039	0.5	59.0
7	55	4.8	4.0	1.1	0.120	3	1.225	2.45	0.24	11.5	35	7.5	.034	0.3	56.0
7	65	4.6	4.0	1.5	0.130	3	0.975	1.75	0.17	11.0	27	8.0	.022	0.2	65.5
7	75	4.8	4.0	2.2	0.141	3	1.125	2.09	0.17	18.5	19	15.0	.024	0.2	68.0
7	85	4.6	3.9	1.6	0.152	6	0.450	2.61	0.19	22.4	20	18.0	.024	0.4	89.5
7	95	4.7	4.0	0.9	0.196	3	1.375	2.27	0.16	20.0	20	16.0	.023	0.2	69.0
7	105	4.9	4.1	1.3	0.413	3	1.400	2.63	0.17	18.1	26	13.5	.020	0.2	68.5
7	115	4.8	4.0	0.9	0.522	3	1.575	3.04	0.20	24.3	22	19.0	.021	0.1	96.0
7	125	4.7	3.9	0.8	0.500	0	1.625	2.94	0.21	21.8	24	16.5	.022	0.2	104.5
7	135	4.7	3.8	0.9	0.652	0	2.025	3.58	0.26	28.0	23	21.5	.025	0.2	100.5

Soil Chemical Properties by 10cm Depths

Pit No.	Depth in cm	pH_w	pH_s	% 0M	Na Meq/100g	$P_2 0_5$ 1bs/ac	Ca meq/100g	Mg meq/100g	K meq/100g	CEC meq/100g	BS %	NAC meq/100g	N % Total	Mn ppm	Al ppm
8	5	4.9	4.2	2.2	0.087	17	0.725	0.60	0.24	5.2	32	3.5	.043	22.7	22.5
8	15	4.9	4.1	1.6	0.087	6	0.600	0.68	0.22	6.6	24	5.0	.039	3.6	30.5
8	25	4.7	4.1	1.3	0.098	8	0.575	2.27	0.23	12.4	23	9.5	.050	1.0	51.5
8	35	4.8	4.1	1.6	0.109	6	0.550	2.54	0.21	13.6	23	10.5	.042	0.5	65.5
8	45	4.8	4.0	1.4	0.130	3	0.525	4.08	0.19	20.4	17	17.0	.034	0.2	134.5
8	55	4.8	4.1	1.0	0.228	3	0.526	4.09	0.28	27.1	19	22.0	.042	0.2	139.5
8	65	4.9	4.1	0.6	0.293	3	0.550	4.45	0.28	27.6	20	22.0	.034	0.2	118.0
8	75	4.9	4.0	0.7	0.315	3	0.425	3.75	0.24	26.8	18	22.0	.030	0.2	160.0
8	85	4.8	4.0	0.5	0.337	3	0.400	3.68	0.26	17.9	18	21.5	.031	0.2	157.5
8	95	4.7	4.0	0.7	0.337	3	0.400	3.83	0.28	25.8	19	21.0	.029	0.2	167.5
8	105	4.7	3.9	0.4	0.435	3	1.200	4.20	0.27	28.1	22	22.0	.027	0.1	143.0
8	115	4.6	3.8	0.9	0.435	3	1.175	4.13	0.26	28.0	21	22.0	.022	0.1	133.0
8	125	4.4	3.8	1.4	0.424	3	1.200	3.83	0.23	25.7	22	20.0	.022	0.1	98.5
8	135	4.4	3.8	1.2	0.413	3	1.250	3.54	0.22	24.4	22	19.0	.021	0.2	104.0
8	145	4.2	3.6	1.3	0.500	3	1.575	4.25	0.27	26.0	25	19.5	.024	0.3	109.5

APPENDIX D

ROOT LENGTH BY 10CM DEPTHS

Root Length by 10cm Depths

Pit No.	Depth cm	Root Length cm/cm^3	Root Length in Percent	Cumulative Percent of Root Length.	Root Weight mg/cm^3	Root Weight in Percent	Cumulative Percent of Root Weight
1	5	1.410	30.57	30.57	5.906	6.18	6.18
1	15	0.280	6.11	36.68	2.432	2.55	8.73
1	25	0.239	5.18	41.86	23.559	24.66	33.39
1	35	0.292	6.33	48.19	5.065	5.30	38.69
1	45	0.342	7.41	55.60	31.383	32.83	71.52
1	55	0.285	6.18	61.78	10.871	11.38	82.90
1	65	0.224	4.86	66.64	1.392	1.46	84.36
1	75	0.258	5.59	72.23	9.441	9.88	94.24
1	85	0.244	5.29	77.52	0.288	0.30	94.54
1	95	0.271	5.87	83.39	3.598	3.77	93.31
1	105	0.270	5.85	89.24	0.389	0.41	98.70
1	115	0.166	3.60	92.84	0.176	0.18	98.90
1	125	0.124	2.69	95.53	0.188	0.20	99.10
1	135	0.206	4.47	100.00	0.865	0.91	100.00

Root Length by 10cm Depths

Pit No.	Depth cm	Root Length cm/cm^3	Root Length in Percent	Cumulative Percent of Root Length.	Root Weight mg/cm^3	Root Weight in Percent	Cumulative Percent of Root Weight
3	5	0.876	15.11	15.11	6.106	22.69	22.69
3	15	0.908	15.67	30.78	3.047	11.32	32.01
3	25	0.504	8.67	39.45	1.943	7.22	41.23
3	35	0.444	7.64	47.09	11.623	43.22	84.45
3	45	0.441	7.59	54.68	0.489	1.82	86.27
3	55	0.430	7.40	62.08	0.414	1.54	87.81
3	65	0.206	3.55	65.63	0.301	1.12	88.93
3	75	0.300	5.16	70.79	0.288	1.07	90.00
3	85	0.320	5.51	76.30	0.865	3.31	93.21
3	95	0.292	5.03	81.33	0.489	1.82	95.03
3	105	0.484	8.33	89.66	0.727	2.70	97.73
3	115	0.325	5.59	95.25	0.238	0.88	98.61
3	125	0.157	2.70	97.95	0.238	0.88	99.49
3	135	0.119	2.05	100.00	0.138	0.51	100.00

Root Length by 10cm Depths

Pit No.	Depth cm	Root length cm/cm^3	Root length in percent	Cumulative Percent of Root Length.	Root Weight mg/cm^3	Root Weight in Percent	Cumulative Percent of Root Weight
4	5	1.779	32.26	32.26	44.636	71.05	71.05
4	15	0.975	17.68	49.94	11.297	17.98	89.03
4	25	0.823	14.93	64.87	1.893	3.01	92.04
4	35	0.458	8.31	73.18	1.016	1.62	93.66
4	45	0.439	7.96	81.14	1.555	2.48	96.14
4	55	0.354	6.42	87.56	1.317	2.10	98.24
4	65	0.231	4.19	91.76	0.489	0.78	99.02
4	75	0.257	4.66	96.41	0.263	0.42	99.44
4	85	0.198	3.59	100.00	0.351	0.56	100.00

Root Length by 10cm Depths

Pit No.	Depth cm	Root length cm/cm^3	Root length in percent	Cumulative Percent of Root Length.	Root Weight mg/cm^3	Root Weight in Percent	Cumulative Percent of Root Weight
5	5	1.258	26.77	26.77	4.652	33.40	33.40
5	15	0.974	20.73	47.50	2.457	17.64	51.04
5	25	0.592	12.60	60.10	1.429	10.26	61.30
5	35	0.292	6.21	66.31	1.166	8.37	69.67
5	45	0.416	8.85	75.16	2.056	14.76	84.43
5	55	0.369	7.85	83.01	0.978	7.02	91.45
5	65	0.194	4.13	87.14	0.376	2.70	94.15
5	75	0.036	0.77	87.91	0.125	0.90	95.05
5	85	0.107	2.28	90.19	0.150	1.08	96.13
5	95	0.110	2.34	92.53	0.113	0.81	96.94
5	105	0.102	2.17	94.70	0.125	0.90	97.84
5	115	0.063	1.34	96.04	0.063	0.45	98.29
5	125	0.064	1.36	97.40	0.113	0.81	99.10
5	135	0.122	2.60	100.00	0.125	0.90	100.00

Root Length by 10cm Depths

Pit No.	Depth cm	Root length cm/cm^3	Root length in percent	Cumulative Percent of Root Length.	Root Weight mg/cm^3	Root Weight in Percent	Cumulative Percent of Root Weight
6	5	2.312	39.50	39.50	8.175	30.78	30.78
6	15	0.569	9.72	49.22	6.808	25.64	56.42
6	25	0.514	8.78	58.00	2.658	10.01	66.43
6	35	0.208	3.55	61.55	1.454	5.48	71.91
6	45	0.367	6.27	67.82	0.652	2.46	74.37
6	55	0.372	6.35	74.17	3.787	14.26	88.63
6	65	0.232	3.98	78.15	0.752	2.83	91.46
6	75	0.203	3.47	81.62	0.451	1.70	93.60
6	85	0.092	1.57	83.19	0.125	0.47	93.63
6	95	0.088	1.50	84.69	0.075	0.28	93.91
6	105	0.107	1.83	86.52	0.251	0.95	94.86
6	115	0.305	5.21	91.73	0.100	0.38	95.24
6	125	0.296	5.06	96.79	0.840	3.16	98.40
6	135	0.188	3.21	100.0	0.426	1.60	100.00
6	145	0.203			0.401		

Root Length by 10cm Depths

Pit No.	Depth cm	Root length cm/cm^3	Root length in percent	Cumulative Percent of Root Length.	Root Weight mg/cm^3	Root Weight in Percent	Cumulative Percent of Root Weight
7	5	2.221	30.90	30.90	7.172	15.14	15.14
7	15	0.994	13.83	44.73	3.889	8.23	23.37
7	25	0.327	4.55	49.28	15.272	32.26	55.63
7	35	0.213	2.96	52.24	1.154	2.44	58.07
7	45	0.290	4.04	56.28	4.978	10.51	68.58
7	55	0.176	2.45	58.73	0.351	0.74	69.32
7	65	0.572	7.96	66.69	3.473	7.33	76.65
7	75	0.517	7.19	73.88	1.041	2.20	78.85
7	85	0.503	7.00	80.88	1.492	3.15	82.00
7	95	0.418	5.82	86.70	0.915	1.93	83.93
7	105	0.301	4.19	90.89	2.044	4.32	88.25
7	115	0.198	2.76	93.65	1.668	3.52	96.77
7	125	0.138	1.92	95.57	2.633	5.56	97.33
7	135	0.318	4.43	100.00	1.266	2.67	100.00

Root Length by 10cm Depths

Pit No.	Depth cm	Root length cm/cm^3	Root length in percent	Cumulative Percent of Root Length	Root Weight mg/cm^3	Root Weight in Percent	Cumulative Percent of Root Weight
8	5	0.928	18.39	18.39	3.247	7.31	7.31
8	15	0.535	10.61	29.00	1.730	3.89	11.20
8	25	0.371	7.36	36.36	3.022	6.80	18.00
8	35	0.326	6.46	42.86	1.492	3.36	21.36
8	45	0.293	5.81	48.63	0.865	1.95	23.31
8	55	0.359	7.12	55.75	1.793	4.04	27.35
8	65	0.163	3.23	58.98	10.143	22.83	50.18
8	75	0.453	8.98	67.96	1.066	2.40	52.58
8	85	0.352	6.98	74.94	17.930	0.34	92.92
8	95	0.227	4.50	79.44	1.429	3.22	96.14
8	105	0.147	2.91	82.35	0.201	0.45	96.59
8	115	0.198	3.93	86.28	0.401	0.90	97.49
8	125	0.303	6.01	92.29	0.263	0.59	98.08
8	135	0.389	7.71	100.00	0.853	1.92	100.00